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An IRU for Cassini*

L L Gresham, E C Litty
Jet Propulsion Laboratory

1' R Toole, D R Beisecker
Litton Guidance & Control, Space Operations

Abstract

The JPL Inertial Reference Unit (IRU) is the single most sophisticated assembly on the Cassini Spacecraft. At the core of the IRU is the stdc-of-the-mt, Litton (formerly Delco) Hemispherical Resonator Gyroscope (HRG). The HRG operation is based on the theory, developed by British physicist G. 11, Bryan**, that the wave pattern developed on the rim of a wine glass when excited vibrates in a stable wave form, even when the glass is rotated about another axis. Utilizing this principle, the HRG consists ofa hemispherical quartz resonating at 4 kHz with an extremely high Q (approximately ten million) excited by a 100 Vctc forcer source. The tympanic shape of the quartz resonator suppresses harmonics such that the fundamental frequency remains virtually uncorrupted by interference. The HRG with no mechanically moving parts uses a capacitive pick-off detection scheme to sense the wave on the quartz. The quartz covered with a metallic laminate is mounted concentrically with the pick-off and forcer rings forming a set of parallel surfaces capable of providing a mechanism for sensing variations in the capacitive coupling (approximately 5 pFs). This coupling is sufficient to detect the precession of the standing wave on the resonator as the gyro senses rotation. The geometry is such that the change in the standing wave precession angle equates to 0.3 times the resonator rotation angle. The resonator, forcer, and pick-off ring are housed within a titanium vessel with a vacuum of' approximately 10 F-07 torr. A getter maintains the vacuum while the HRG is in the atmosphere.

The spacecraft will be launched in November/December opportunity 1997 traveling approximately 7 yrs to meet its Saturn object ives in the year 2004. At Saturn the spacecraft will be maneuvered into a nearly circular low altitude orbit to position for mapping from ? to ? During this period repetitive observations of the planet will be conducted from a ? km, _ degree orbit with a Saturn day cycle. At the end or during the mapping phase?, the spacecraft will transmit scientific information to the Earth. Following the low activity cruise phase, the IRU will facilitate pointing during the repetitive mapping passes over Saturn without interference to the instruments.

The objectives of the mission are the scientific investigation of the planet's surface and rings, atmosphere, gravitational and magnetic fields. The Cassini spacecraft constantly must reposition during mapping to form the 3-axes stabilized platform for the instrument payloads to perform these quests. The Cassini IRU contains gyros for measuring the angular rates. These measurements are used to fix and stabilize the inertial pointing during maneuvers and measure yaw attitude during mapping phase. Attitude determination software uses this information in conjunction with the stellar sensor reference unit during mapping for relating the nadir pointing direction to the inertial reference.

* The work described within this paper was sponsored by the Jet Propulsion laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration.

** Based on the investigation and theory developed by (i 11 Bryan, Cambridge , England, 1X9(I

The I Iemispherical Resonator Gyroscope -- An IRU for Cassini*

Edward C. Litty, Lennor L. (ire.dmm (Jet Propulsion Laboratory, California Institute of Technology), Patrick Toole, Deborah Beisecker (Litton Guidance and Control Systems, Space Operat ions)

Abstract. ***The JPL Inertial Reference Unit (IRU) is the single most sophisticated assembly on th e Cassini Spacecraft. At th e core of th e IRU is the stde-of-the-m-t, Litton (formerly Delco) Hemispherical Resonator Gyroscope (HRG).*** Launched in October 1997, Cassini's trajectory utilizes gravity assist maneuvers around Venus (twice), Earth, and Jupiter over a seven year period, arriving at Saturn in June 2004, Its tour of the Saturnian system will last an additional four years. Although the Stellar Reference Unit (SRU) provides the ultimate reference for the spacecraft Attitude and Articulation Control System (AACS) and can be used to control the spacecraft under benign conditions, the Cassini inertial Reference Unit (1 RU) will be essential for precision attitude stabilization during maneuvers and fault recovery operations. The reliability of the IRU over the long Cassini mission is therefore of critical concern.

Following an extensive evaluation of several possible alternatives the I hemispherical Resonator Gyro (1 IRG) based IRU, developed by Litton Guidance and Control Systems, was chosen for the Cassini mission. The HRG offers an attitude sensor that has no physical wear-out mechanisms. Based on a principle first described by G. H. Bryan (1 890) in his paper, "On Beats in the Vibrations of a Revolving Cylinder or Bell", the HRG is created by vibrating a quartz resonator. This paper discusses the theory and modifications required to the design of the standard Space 1 RU (SIRU) with embedded I IRGs to adapt it to meet the unique requirements of the Cassini mission and the AACS interface. The Cassini IRU will be the first usc of an IRU for a deep space planetary mission that dots not usc a spun mass sensor.

Introduction

The 1 IRG operation is based on the theory, developed by British physicist G. 11. Bryan (Ref. 1). A wave pattern developed on the rim of a wine glass when excited vibrates in a stable wave form, even when the glass is rotated about another axis as shown in Figure 1. Utilizing this principle, the 1 IRG consists of a hemispherical quartz resonating at 4.1 kHz with an extremely high Q (approximately ten million) excited by a 100 Vdc forcer source. The tympanic shape of the quartz resonator suppresses harmonics such that the fundamental frequency remains virtually uncorrupted by interference. The 11 RG with no mechanically moving parts uses a capacitive pick-off detection scheme to sense the change in the electrostatic forces with reference to points of maximum Coriolis forces (known as antinodes) developed on the quartz rim as it vibrates. The quartz, covered with a metallic laminate, is mounted concentrically with the pick-off and forcer rings forming a set of parallel surfaces capable of sensing variations in the capacitive coupling (approximately 5 pFs). This coupling is sufficient to detect the precession of the standing wave on the resonator as the gyro senses rotation. The geometry is such that the change in the standing wave precession angle equates to 0.3 times the resonator rotation angle. The resonator, forcer, and pick-off ring arc housed within a titanium vessel (Figure 2) evacuated to approximately 10 E-07 Torr.

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The spacecraft (5,650 kg) is scheduled for launch on a Titan IV-Centaur in the October 1997 window of opportunit y traveling approximately 7 yrs to meet its Saturn object ives in the year 2004. Using four planet flybys (two around Venus, one around Earth and onc around Jupiter) to increase the speed of the spacecraft using these planets' gravitational fields, the craft will reach Saturn 1.43 Terameters away from the Sun. Following the low activity cruise phase, the IRU will facilitate pointing during the repetitive mapping passes over Saturn without interference to the instruments. The spacecraft performs maneuvers at low Saturn altitude, approximately 20,000 km, positioning and repositioning for mapping throughout nearly 60 repetitive orbits around the planet covering both the equatorial and polar zones. Note that the Saturn upper atmosphere is primarily composed of hydrogen, helium, and ammonia. During the mission, Cassini will execute flybys of a set of icy satellites, Titan and other Saturnian moons, In late 20041 Iuygens probe will be released for its perhaps fateful descent, two and a half hours, through Titan's dense atmosphere while relaying data back to the Cassini orbiter to be stored and downlinked to the Earth. During downlink phases, the spacecraft will be repositioned to transmit scientific information to the Earth via the Deep Space Antenna Network,

The objectives of the mission are the scientific investigation of the planet's surface, its moons and rings, and the composition of the Saturnian atmosphere, the infrared energy, plasma, gravitational and magnetic fields. The Cassini spacecraft constantly must reposition during mapping to form the 3-axes stabilized platform for the instrument payloads to perform these quests. The Cassini single string redundant IRUs each contains four gyros for measuring angular rates. Either IRU can be utilized to provide attitude control reference. And within each 1 RU, only three of the four gyros are required for normal operation The measurements are used to fix and stabilize the inertial pointing during maneuvers and measure yaw attitude during the mapping phase. Attitude determination software uses this information in conjunction with the stellar sensor reference unit during mapping for relating the nadir pointing direction to the inertial reference.

Configuration of the Inertial Reference Unit

The 1 IRG consists of a resonator, forcer, and pick-off bonded and contained within a sealed vacuum housing. Since the gyros operate in a vacuum, space is a natural environment for the IRU 11 RGs. The buffer amplifier circuit is attached to the sealed gyro housing to amplify the pick-off signals. The complete HRG130Y assembly, including the b u ffer amplifier, weighs approximately 0.3 pounds and measures approximately 6 cms in height and width, '1'here are no moving mechanical parts in the IRU except for the minuscule amplitude vibration on the resonator,

The } IRG detection and control electronics consist of analog signal conditioning circuits, an analog-to-digital interface, and digital signal processors. Four control loops determine the "force-to-rebalance" mechanization used in the IRU system. These arc: 1) a phase lock loop that tracks the natural resonant frequency of the quartz dome; 2) an amplitude control loop that maintains the nominal resonator flex amplitude; 3) the quadrature control loop used to correct for small mass imbalances that occur on the resonator, and 4) a rate loop that applies the "rebalance" torque forcing the vibration pattern to remain nodal stationary.

The Cassini IRU as shown in Figure 3 is composed of four HRGs sensing 3 orthogonal axes and one skew axis. The unit consists of a power converter to regulate the 30 Vdc spacecraft power bus, two Sensor Electronics Module (SEM) cards, two microprocessor chips for signal processing, and the IRU operations Flight Software (OFP) required to initialize, signal process, and format data communicated via the Remote Terminal input/Output Unit (RTIOU) on the 1553B bus to the Attitude and Articulation Control System (AACS) Flight Computer. The AACS software performs alignment and bias calibrations during flight. An 1{ S-422 interface is provided for test and rate simulation, but this interface is not connected in flight.

The Cassini SEM cards contain the gyro signal processor, 8 MIPs with 24 bit words, the input/output controller, 8 MIPs with 16 bit words, and Memory consisting of SRAM with 128 kbytes of 24 bit words and ROM with 128 kbytes of 16 bit words. Unlike the original SIRU, the Cassini SEM ROMs arc PROMS instead of EEPROMs. 'l'his exchange of EEPROMs to more reliable radiation-hardened PROMS was onc of several design enhancements made in consideration of the harsh environment of this mission (i. e., approximately 100 kRADs Total Ionization Dosage, 13 yrs life, and temperature excursions from -35 to 75°C), as well as, weight, size, and power limitations, and reliability that required a unique IRU for Cassini. "A step back to the future" of the original CRAF/Cassini Mission, will perhaps provide a clearer understanding of the evolution of the Cassini IRU and its unique attributes.

Choosing **an IRU for Cassini. The** first issue that should bc addressed prior to any discussion about the Inertial Reference Unit (IRU) used on the Cassini Mission is: "DO wc need one at all?". During parts of the cruise phase, the IRU is, in fact, not required for normal operation, since the Star Tracker (later termed the Stellar Reference Unit, SRU) provides both the attitude reference and dynamic rates of the spacecraft that allow relatively low rate information for attitude control. Under such circumstances the spacecraft can maintain communications with the Earth, adjusting the attitude as required to keep the High Gain Antenna (HGA) in the required field of view (FOV), while compensating for environmental disturbances such as solar wind which affects pointing.

However, most of Cassini's operational modes do require the usc of an IRU. Even when conditions have been benign, it may bc necessary for the spacecraft to react quickly to conditions such as the effects of an actual or perceived equipment failure which would exceed the ability of the Star Tracker to control the spacecraft. An IRU is also required for Trajectory Correction Maneuvers (TCM's), when the spacecraft must turn to a ncw attitude, control the attitude during the time the engines arc thrusting (using the Engine Gimbal Actuators to control the attitude, which may change rapidly under these conditions), and return to the original attitude. Particularly during the science acquisition phase of the mission, the IRU is required to provide a tightly controlled attitude in order for the instruments to acquire precise data to achieve maximum resolution. Additionally it may bc necessary to limit the transient attitude effects of different instruments operating simultaneously. For all of these uses, the Star Tracker provides the absolute attitude reference for the IRU, which has no knowledge of the absolute attitude, but can measure the change in attitude, even when such changes occur rapidly, Since there arc error sources in the IRU that accumulate with time, such as bias drift, this reference "update" must be supplied periodically to allow error sources to bc minimized. This "partnership" between the IRU and Star Tracker for precision pointing on a large gimbal, called the High Precision Actuator (HPA), provides the platform for instruments to acquire data with ultimate resolution, The proposed Star Tracker has a relatively small field of view (2.8 x 2.8 degrees), so the strategy was to use the HPA to occasionally point the Star Tracker to a suitable star, or pair of stars, to obtain attitude updates. This data allows the attitude determination algorithms to propagate an estimate of spacecraft attitude that would be sufficiently accurate at any point in time. The bias drift rate performance of the IRU, the rate the IRU "sees" when it is not actually turning, directly determines the length of time that can be allowed between updates.

The performance requirements for the IRU, determined by considering the above factors, originally led to the consideration of an inertial grade attitude sensor, such as the dry tuned gyro unit (DRIRU 11) or others of this class. A serious concern was the lifetime requirement, in excess of 17 yrs including test, shelf, and mission time. Since adequate life test prior to launch was impossible, it was desirable to have a unit with "heritage" with reliability demonstrated to the maximum extent possible. Although such sensors have exhibited the required lifetime, the total number of examples is still relatively small, particularly since mechanical components such as bearings and retainers have been used in this class of sensors in the past,

In 1992 extreme pressure to reduce cost and spacecraft mass led to new strategies. The HPA, as well as, the Turn Table Assembly (TTA), a spinning platform for instruments measuring fields and particles, were both eliminated from the Cassini design. The entire complement of instruments and the Star Tracker were to be hard mounted to the spacecraft bus, where they would be pointed by moving the entire spacecraft; hence, the spacecraft itself became the stable platform. This tremendous change in the spacecraft design had dramatic ramifications affecting the attitude determination process. The turn rates that could be supported by the reaction wheel were much slower than the slew rates of the HPA, so the process of getting star updates could take appreciably longer. Preliminary estimates revealed that the star identification and the reference process could require up to 30 minutes every two hours--the science observations would be drastically reduced. The science community was devastated. Plus during the cruise phase, the Star Tracker would be used to track a star which would generally not allow downlink to Earth (originally to be performed weekly), so the IRU would need to be powered on and the spacecraft attitude changed for downlink, increasing the required IRU lifetime and the number of on/off cycles. The entire spacecraft would need to be rolled for the fields and particles instruments, and the roll would have to be periodically interrupted to get star updates. As a result of these insurmountable problems, the Star Tracker was replaced with the Stellar Reference Unit (SRU), a new design star tracker with 15 x 15 degrees FOV. The wider FOV generally allows three-axes updates without reorienting the SRU pointing, which allows much more frequent attitude updates. The performance requirement for bias drift was therefore substantially reduced, creating the possibility of a less accurate, but lighter and perhaps cheaper IRU.

As a result of the above changes, potential vendors were queried. A Request for information (RFI) was released to a wide range of potential contractors to determine the availability of IRU's which could satisfy our new requirements. It should be noted here that although the performance requirements had been relaxed, the IRU was still essential for the Cassini mission, so reliability and life considerations were still extremely important, The preliminary proposed specification was written to allow the possibility of alternatives to the usual spun mass technology gyros traditionally used on spacecraft, and it was considered that the performance requirements could enable the use of tactical grade IRU's, provided that the reliability issues could be satisfied.

The response to the RFI indicated that a wide range of IRU's might be available with the potential to satisfy the Cassini requirements. Considering this outcome, JPL proceeded to develop a formal Request for Proposal (RFP) package with a more detailed specification that still allowed the widest range of IRU types possible,]n addition, the details of the JPL reliability requirements for a Class A mission were provided, including the radiation environments to be expected. The RFP was distributed to the vendors who had indicated an interest in response to the RF], The proposed contract type was to be Firm Fixed Price, and the procurement was to be competitive.

Several proposals to the IRU RFP were received, utilizing spun mass gyros, ring laser gyros, and the hemispherical resonator gyro. A competitive evaluation was performed, which compared the proposals in the areas of cost, technical performance, heritage, programmatic factors, schedule, and risk. The evaluation process was difficult, since most of the proposed IRU's were close to each other with respect to satisfying the RFP, although there were significant differences in the approach used. At the end of this process the unit chosen was the Hemispherical Resonator Gyro based IRU, built by Delco-Hughes, now Litton Guidance and Control Systems, Space Operations, Goleta, CA. The IRU proposed by Litton for use on the Cassini mission was based on a design developed for use on an Earth orbiter.

Several changes to this heritage design were made to enhance the Litton Space Inertial Reference Unit (SIRU) for use on the Cassini mission. The first of these changes had to do with the EEPROM used to store the software used by the IRU's imbedded processors. The Operational Flight Program (OFF') is stored in the EEPROM, and is downloaded into the IRU Random Access Memory (RAM) when the IRU is powered, investigation showed that the ability of these parts to retain the program was questionable when the life and radiation requirements were taken into account. The life requirement for Cassini was 17 yrs (prelaunch and mission life), and the estimated radiation environment was 100 kRADs '1'1 D. While testing could have validated the use the EEPROM's under the proposed conditions, there was insufficient time in the schedule to complete meaningful testing. As a result, the EEPROM was replaced with a fusible link PROM, the RI 16617, which was configured to retain some of the input/output (1/0) software and a small program with sufficient capability to download the main part of the program from the spacecraft through the Attitude and Articulation Control Subsystem (AACS) bus, a serial 15S3 type link to the AACS computer. The RI 16617 has been qualified for use on the Cassini mission through extensive testing Although an impact to the AACS flight software, both in size and complexity, the PROM eliminates the potential risk associated with the EEPROM.

Although the heritage design featured a standard 1553 bus intcl-face, the Cassini AACS design uses a custom 1553 bus (for reasons of power reduction and fault protection), with a JPL developed bus interface unit, the Remote Terminal Input Output Unit (RTIOU). The RTIOU, with an embedded processor, is used throughout the AACS for all the peripherals and its use was specified as part of the RFP. Fortunately, the design of the IRU's 1553 interface was such that the use of the JPL RTIOU could be accommodated with minimal impact to the design.

The architecture of the heritage IRU featured four HRG sensors, arranged with 3 units mutually orthogonal and a fourth unit skewed equally to the other three. The electronics consists of two redundant Electronics Modules (SEM) and two redundant Power Supply Modules (PS) which can be switched to eliminate all single point failures, if the correct set of components is selected. Selection is performed by the use of relays to switch power and signal paths, but it may not be obvious which components should be chosen. Although this is a viable design for many Earth ol-biters, which often have alternate sensors, such as horizon sensors, that can be used to stabilize the spacecraft while the IRU is reconfigured in the event of a failure. Such reconfiguration can usually be accomplished from the ground, since rapid communication is possible in most cases. The Cassini spacecraft, however, will spend much of its life in deep space where the only alternative sensors (the SRU and the sun sensor) may not be usable due to high rates. In addition, the communications link may have excessive light time delays and must depend on the spacecraft attitude being consistent with the antenna in use, To simplify the Cassini AACS fault protection design, the architecture was changed to create two units each of which contain the four HRG units, configured as described above, and a set of single string electronics. This provides a redundant IRU that is completely independent, whose instant use requires no guesswork as to the nature of the failure in the primary equipment, which can independently verify the accurate operation of all axes of attitude information by property comparing the four channel outputs.

operation of the HRG

Operation of the HRG requires four precision control loops; i.e., the 1) Frequency Controller, 2) Amplitude Controller, 3) Rate Controller, 4) the Quadrature Controller. Figures 4-7 illustrate the functional diagrams of these four control loops.

Frequency Controller. The resonator drive signals that control the HRG are synchronized to the natural frequency of the quartz resonator. For the elliptical mode of operation required, the natural resonance is approximately 4.1 kHz. A phase lock loop technique is utilized in order to synchronize the amplitude, quadrature, and rate control loops.

Amplitude Controller. The amplitude controller drives the flex wave amplitude to a reference set point. The amplitude of the flex wave excites the resonator to approximately 100 micro-inches. The amplitude of the flex wave is sensed using the antinodal pick-off buffer and comparing with the reference. A fixed dc voltage is applied to the resonator, and signals from the four nodal and four antinodal points of the standing wave pattern are detected as shown in Figure 5.

Rate Controller. The rate control loop (Figure 6) extracts the inertial rate component by utilizing the "force-to-rebalance" (FTR) technique. The rate controller nulls the in-phase nodal buffer output by generating a rate drive signal to the resonator through the rate forcer capacitive pads. Notice that the gyro mechanics are designated as K{]'(s)}, the scale factor times the dynamics of the plant to yield the in-phase nodal amplitude (y) to voltage and inertial inputs. Noise sources include the instrument's inherent bias and the thermal noise, NIB and NTH respectively. The pick-off gain (Gp) is a very high value that yields angular resolution to less than 1 mini-arc second. The gyro output compensation is a function of temperature, the mode, and the digital rate control, f(T, M, V). The resonant frequency of the gyro is highly stable and linear with temperature. Hence, it is used as an accurate, local reference for the temperature within the shell. Compensation is required for errors contributed by electronic devices, such as analog-to-digital converters that increase the process noise in the readout.

Quadrature Controller. Variations in the resonator mass causes precession errors that occur ninety degrees out-of-phase with the inertial input rate. in order to achieve precision gyro performance, the quadrature control signal suppresses these errors.

Performance and Test Results of the Cassini IRU

For 1 IRG operation two requirements are to: 1) Sustain continuously the standing wave vibration on the lip of the resonator, and 2) Determine the location of the standing wave pattern with relation to a fixed reference. These functions arc implemented by the resonator, the forcer, and the pick-off ring. The 30 mm diameter resonator (130Y HRG) is driven and controlled electrostatically by forcer electrodes. The location and amplitude of the flexing pattern on the resonator are sensed electrostatically by pick-off elect I-odes. By energizing the forcer, a resonating standing wave is excited on the rim of the resonator. The standing wave location, an indicator of the rotation angle, is detected by the pick-offs, which act as variable capacitors providing the wave location data, This data is transformed by a buffer that provides high-input impedance signal conditioning, The gyro is installed in a vacuum housing using a getter. Calibration testing of the gyro is done to check and tune the resonant frequency and assure high quality (Q) and low damping of the resonator. Once the gyros and electronics arc packaged in the IRU assembly, precalibration of the gyro scale factors, initial performance measurements, thermal vacuum, vibration, and final performance tests are performed,

Conclusions

The recent challenge to develop spacecraft in a faster, less expensive, but more demanding performance mode, has required the emergence of new technologies in key subsystems, such as the attitude and articulation and guidance pointing systems. Certainly Litton Guidance and Control Systems, Space Operations, Goleta, CA, has been dynamically leading a new technology in the hemispherical resonant gyros. The combination of stable materials, simple construction, modern electronics, no moving parts, small size, high accuracy, and natural operation in a vacuum environment suggest the HRG as an ideal choice for spacecraft applications. The Cassini IRU will serve as a test of the effectiveness of this innovative technology in a very harsh environment for a 13 year mission to investigate Saturn and its rings.

References

G. 11. Bryan, "On Beats in the Vibrations of a Revolving Cylinder or Bell", Cambridge, England, 1890

Figure 1. **Components of the Hemispherical Resonator Gyroscope**

Figure 2. Basic HRG operation with antinode and Coriolis forces shown during excitation.

Figure 3. **Configuration of the Inertial Reference Unit**

Figure 4. **Operation of the HRG Frequency Controller**

Figure 5. **Representation of the Amplitude Controller**

Figure 6. **Representation of the Rate Controller**

Figure 7. **The Quadrature Controller**

HRG – Exploded View

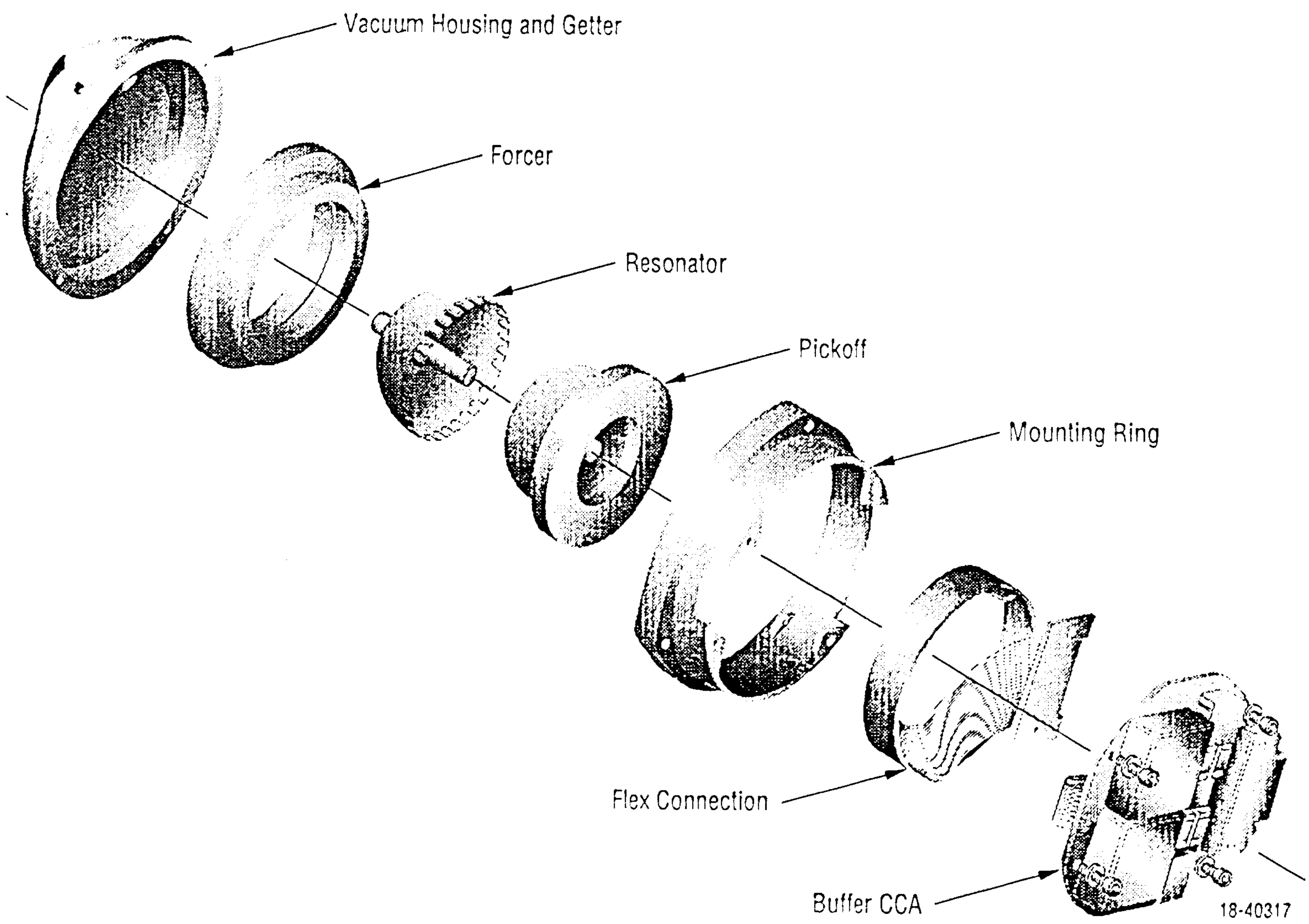


Fig 1

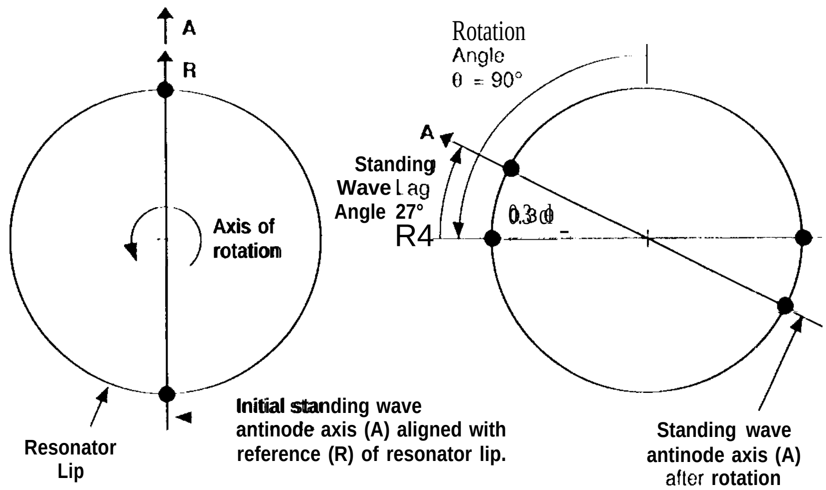
How the HRG functions

1 he rotation-sensing property of a ringing wineglass was first recognized in 1890 by G.H. Bryan, a British physicist. 1 he Hemispherical Resonator Gyro, which is derived from Bryan's ringing wineglass principle, is the basis for a new generation of inertial systems being developed at Delco for aircraft, space launch vehicles, spacecraft, and tactical missiles.

Here's the principle Bryan discovered and how the HRG uses it:

- A ringing or standing wave pattern is sustained on the rim of the resonator.
- At left below, one antinode axis (A) is initially aligned with a resonator reference point (R).
- When the resonator is rotated *90°*, the antinode axis (A) lags behind the rotation of the resonator, as shown below right.

  The ratio of lag angle to rotation angle is a physical constant of the resonator's shape. For a hemisphere, the lag angle is 30°/0 of the rotation.
- In the HRG, pickoff sensors measure the lag angle of the standing wave pattern relative to the resonator to produce the instrument's output signal.



Sales Department
Delco Systems Operations
Delco Electronics ['corporation
6767 Hollister Avenue
Goleta, ('A 93117
1elefon: 001-805-961-5903
1elefax: 001-805 -961 -5416

Sales Representative
Delco Systems Operations
Delco Electronics Corporation
c/o HAISC
Berkenlaan, 1
Box ?, 3rcl Floor
B-1831 Diegem
Belgium
1elefon: 32-2-725-7979
1elefax: 32-2-725-7271

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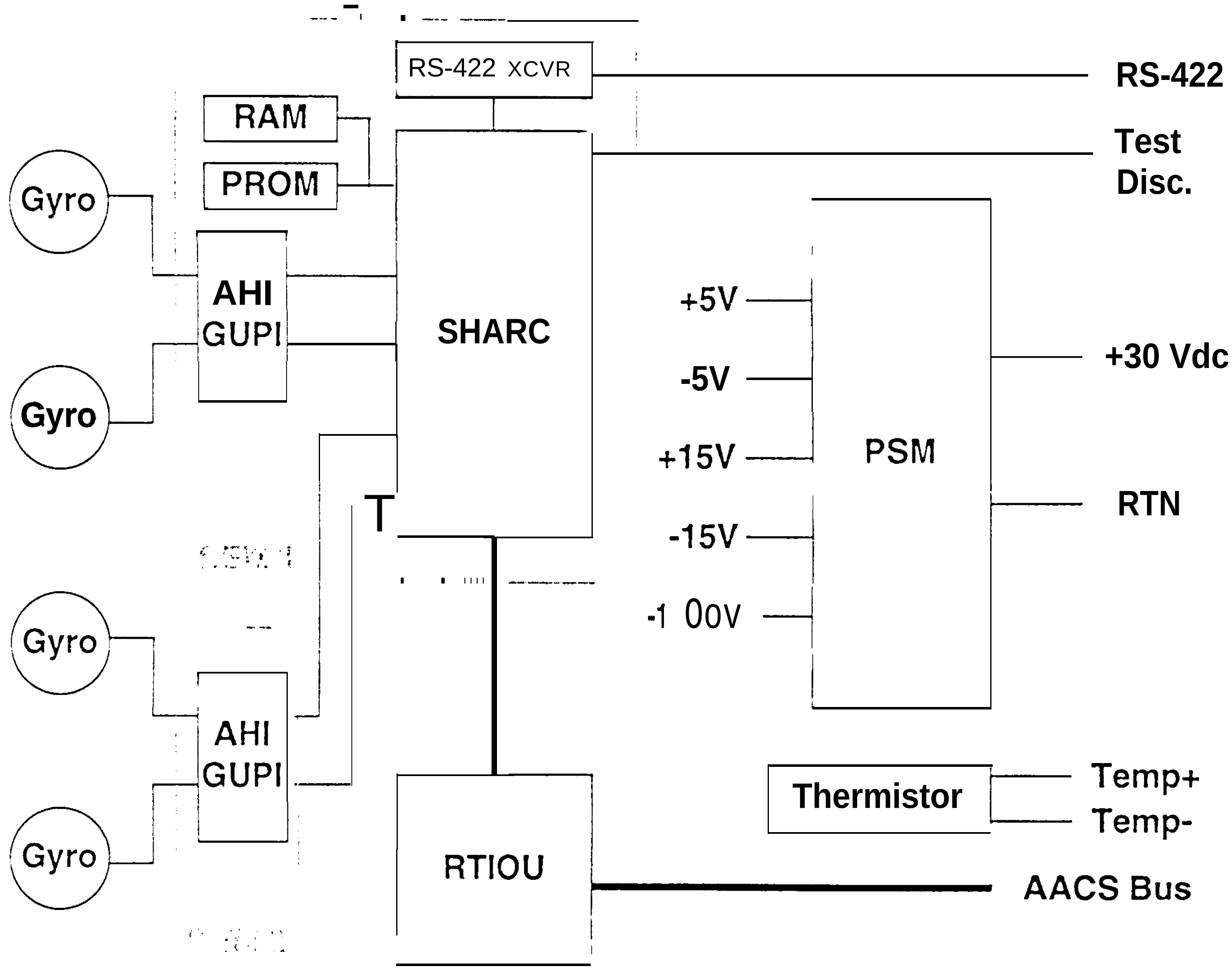
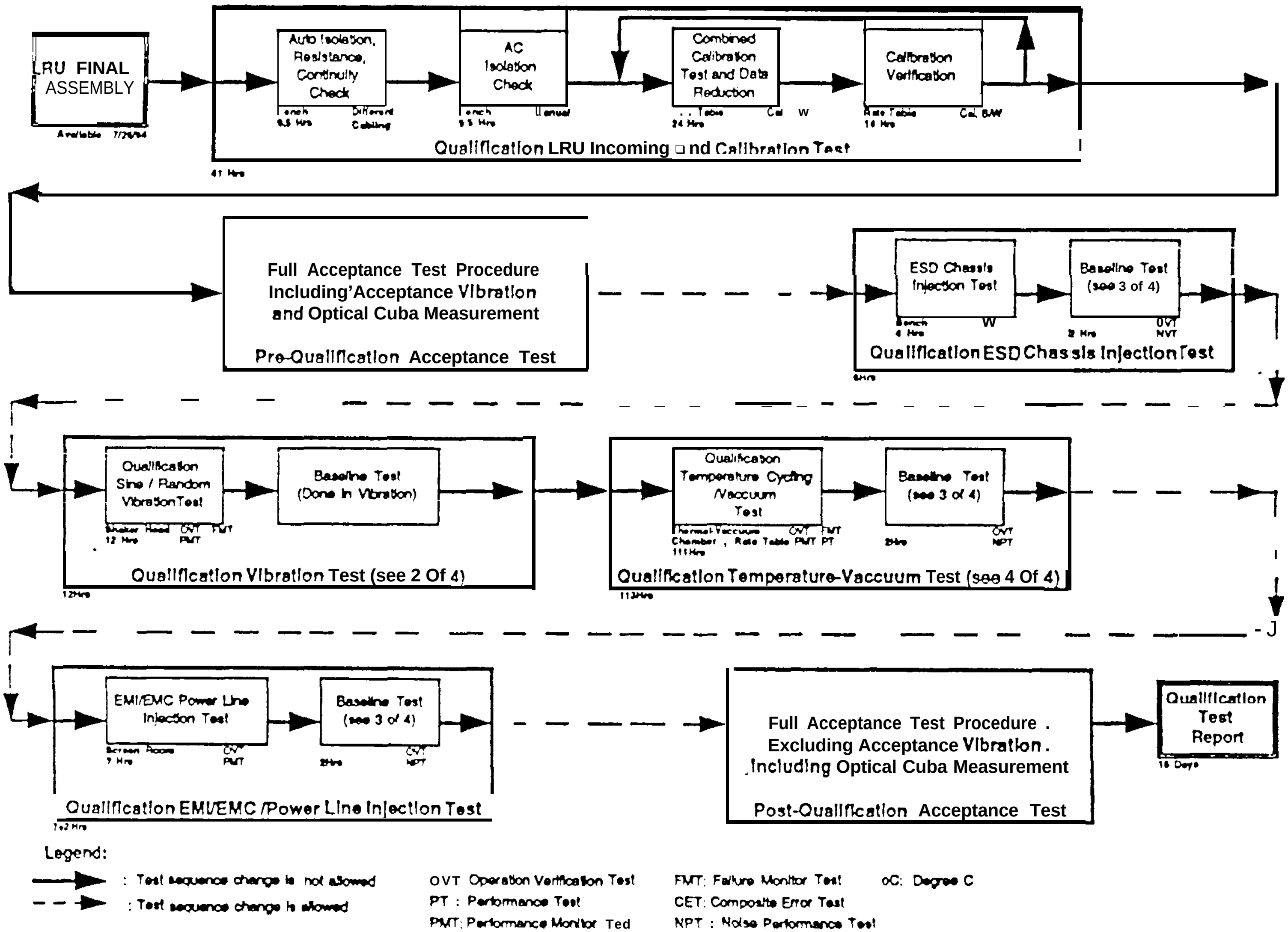
Fig. 2

Cassini IRU Mechanization



SIRU Qualification Test Sequence



Open Loop Quadrature and Parametric Driver Block Diagram

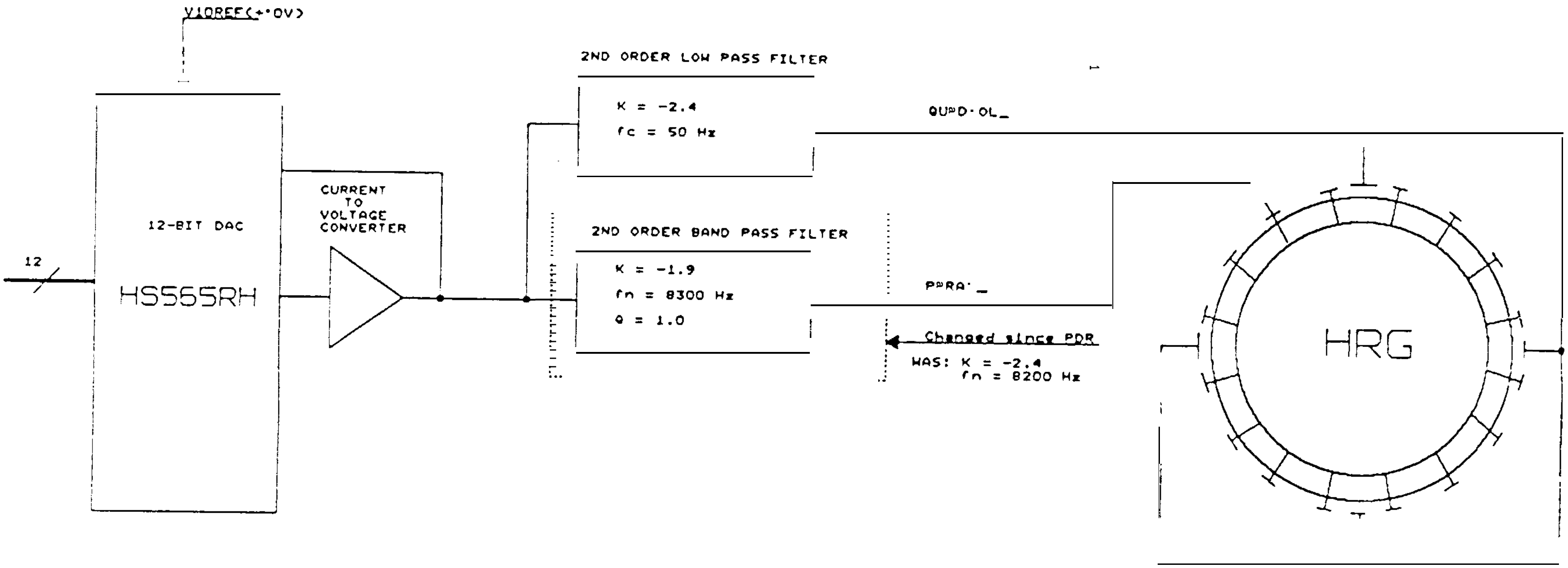


Figure 5

Rate Driver Block Diagram

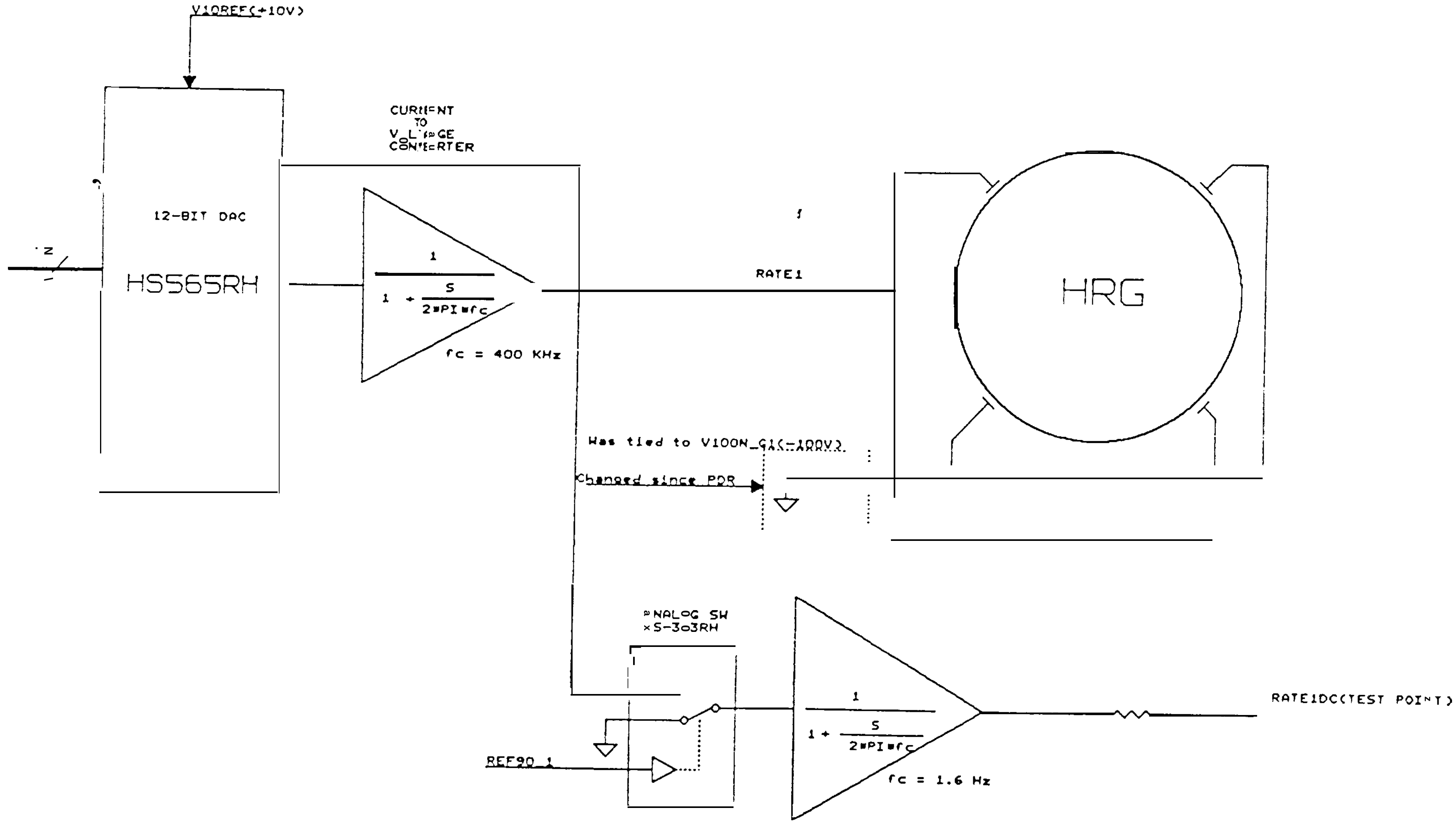
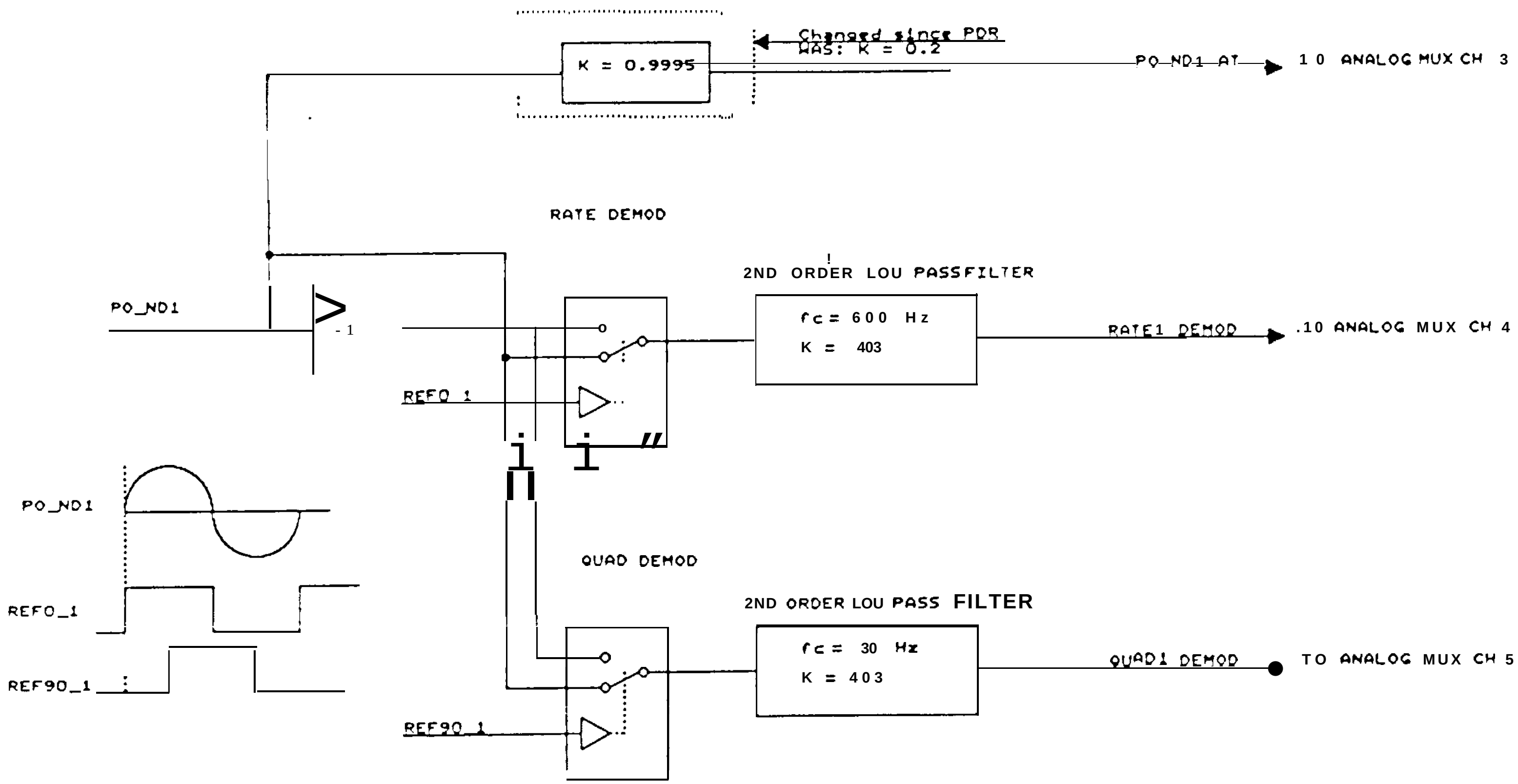


Figure 6

Rate and Quadrature Demodulator Block Diagram

Figure 7



VIEWGRAPH
PACKAGE

International Society for Opical Engineering (SPIE) Anual Meeting: International Symposium on Optical Science, Engineering, and Instrumentation, Lecture, August 6, 1996, Denver, CO, Cochairman: James B. Breckinridge, JPL

1. Session: DENVER96 (Linda Horn) Cassini/Huygens: A mission to the Saturnian System

2. Title: The HRG - An IRU for Cassini

3. Authors: Lennor L. Gresham (JPL), Ed ward C. Litty (JPL), Patrick Toole (Litton GCS), and Deborah Beisecker (Litton GCS)

Addresses:

1.. Gresham: Jet Propulsion Laboratory, **M/S** 301-4664800 Oak Grove Drive Pasadena, CA 91 109(818) 354-6974, FAX: (818) 393-4699, email: L.L.Gresham@jpl.nasa.gov
E. Litty: Jet Propulsion Laboratory, M/S 2514800 Oak Grove Drive Pasadena, CA 91109, (818) 354-5679, FAX: (81 8) 393-4106, email: E.C.Litty@jpl.nasa.gov
P. Toole: Litton Guidance& Control Systems, 67691 Iollister Avenue, Goleta, CA 93117 (805) 961-6359, FAX: (805) 961-7297, email: C43ptoole@cc.dso. hac.com
D. Beisecker, Litton Guidance& Control Systems, 6769 Hollister Avenue, Goleta, CA 93117, (805) 961-6343, , FAX: (805) 961-7237, email: C43dbeiseck@cc. dso.hac.com

s. Abstract& Oral Presentation: **An IRU for Cassini***

The JPL Inertial Reference Unit (IRU) is the single most sophisticated assembly on the Cassini Spacecraft. At the core of the IRU is the state-of-the-art, Litton (formerly Delco) Hemispherical Resonator Gyroscope (HRG). Launched in October of 1997, Cassini's trajectory utilizes gravity assist maneuvers around Venus (twice), Earth, and Jupiter over a seven year period, arriving at the Saturn system in June of 2004. Its tour of the Saturn system will last an additional four years. Although the Cassini Star Reference Unit (SRU) provides the ultimate reference for the spacecraft Attitude and Articulation Control System (AACS) and can be used to cent rol the spacecraft under benign conditions, the Cassini Inertial Reference Unit (IRU) will be essential for precision attitude stabilization and during maneuvers and fault recovery operations. The reliability of the IRU over the long Cassini mission is therefore of critical concern,

Following an extensive evaluation of several possible alternatives the Hemispherical Resonator Gyro (i IRG) based IRU, developed by Litton Guidance and Control Systems, was chosen for the Cassini mission, The Hemispherical Resonator Gyro (HRG) offers an attitude sensor that has no physical wearout mechanisms, based on a principle first described by G. H. Bryan in 1890 in his paper "On Beats in the Vibrations of a Revolving Cylinder or Bell". Modifications to the basic HRG IRU design were made to adapt it to the unique requirements of the Cassini mission and the AACS interface. The Cassini IRU will be the first usc of an lRU for a deep space planetary mission that does not use a spun mass sensor.

*The work described within this paper was sponsored by the Jet Propul sion Laboratory, California institute of Technology, under contract to the National Aeronautics and Space Administration.

6. Key Words: Cassini Mission, Inertial Reference Systems, Hemispherical Resonator Gyro, HRG.

Cassini Inertial Reference Unit

An IRU for Cassini*

06 August 1996
SPIE Conference, Denver, CO

L L Gresham, E C Litty
Jet Propulsion Laboratory

P R Toole, D R Beisecker
Litton Guidance & Control, Space Operations

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SIRU Requirements

Unit	Alignment Accuracy
External Optical Cube (Required	Orthogonality within 5 arc-s
Cube/Unit Mounting Interface (Mount)	±3,600 arc-s
Gyro/Mount	±3,600 arc-s
Gyro/Cube	Measured within ±20 arc-s

Key IRU Requirements

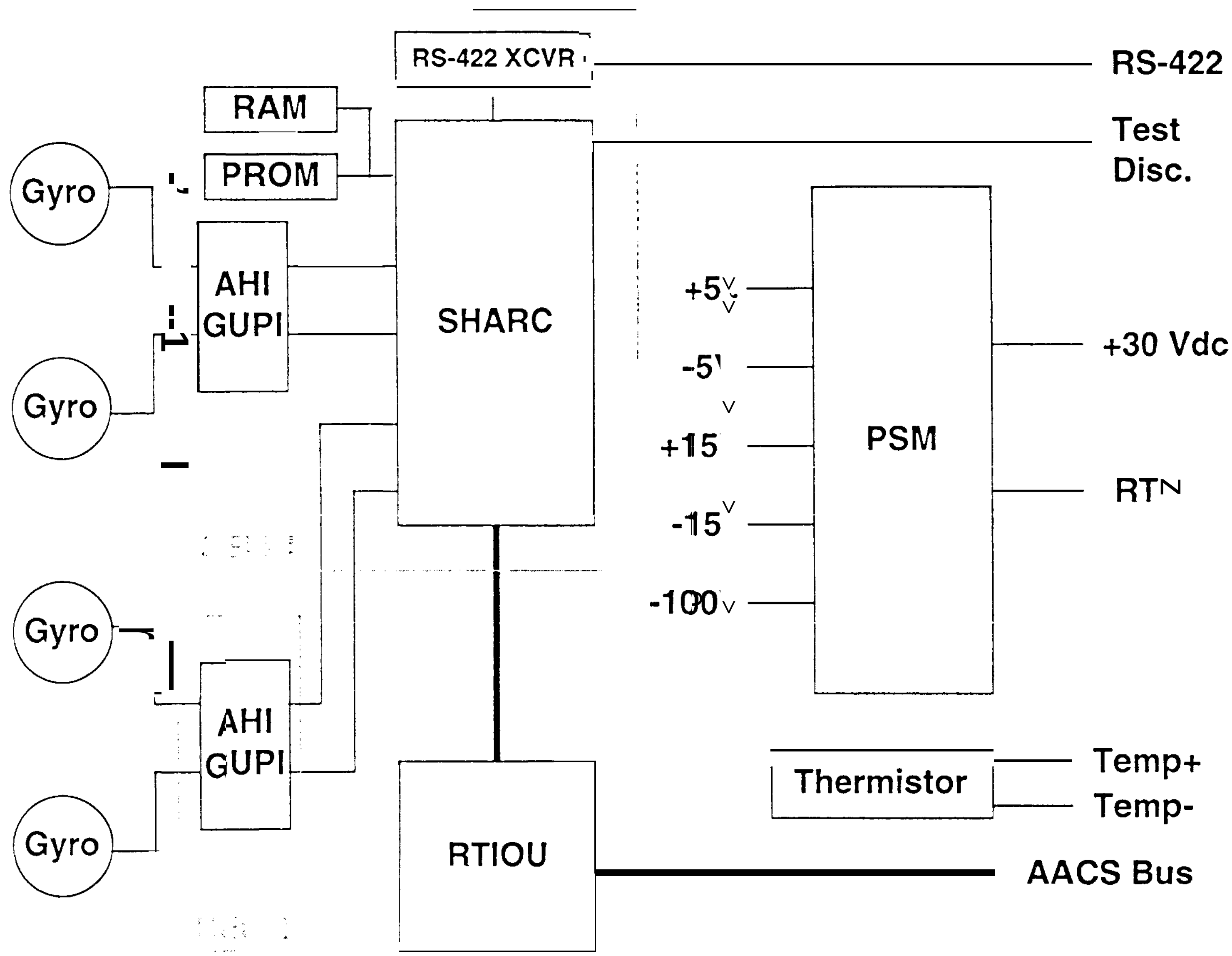
Per JPL ES51 6188,22 April 93

- Employ sensors capable of measuring angular rates about the **3** major orthogonal axes of the spacecraft
- Meet performance in space environment: radiation, thermal, and vacuum
- Sustain 15-year useful ife (12.5-year mission)
- Contain sufficient redur dant elements to avoid loss of angular data due to single failures
- Incorporate RTIOU interface to AACS bus
- Consume 26 W maximum power (without redundant channels operating)
- Weigh 20 kg maximum

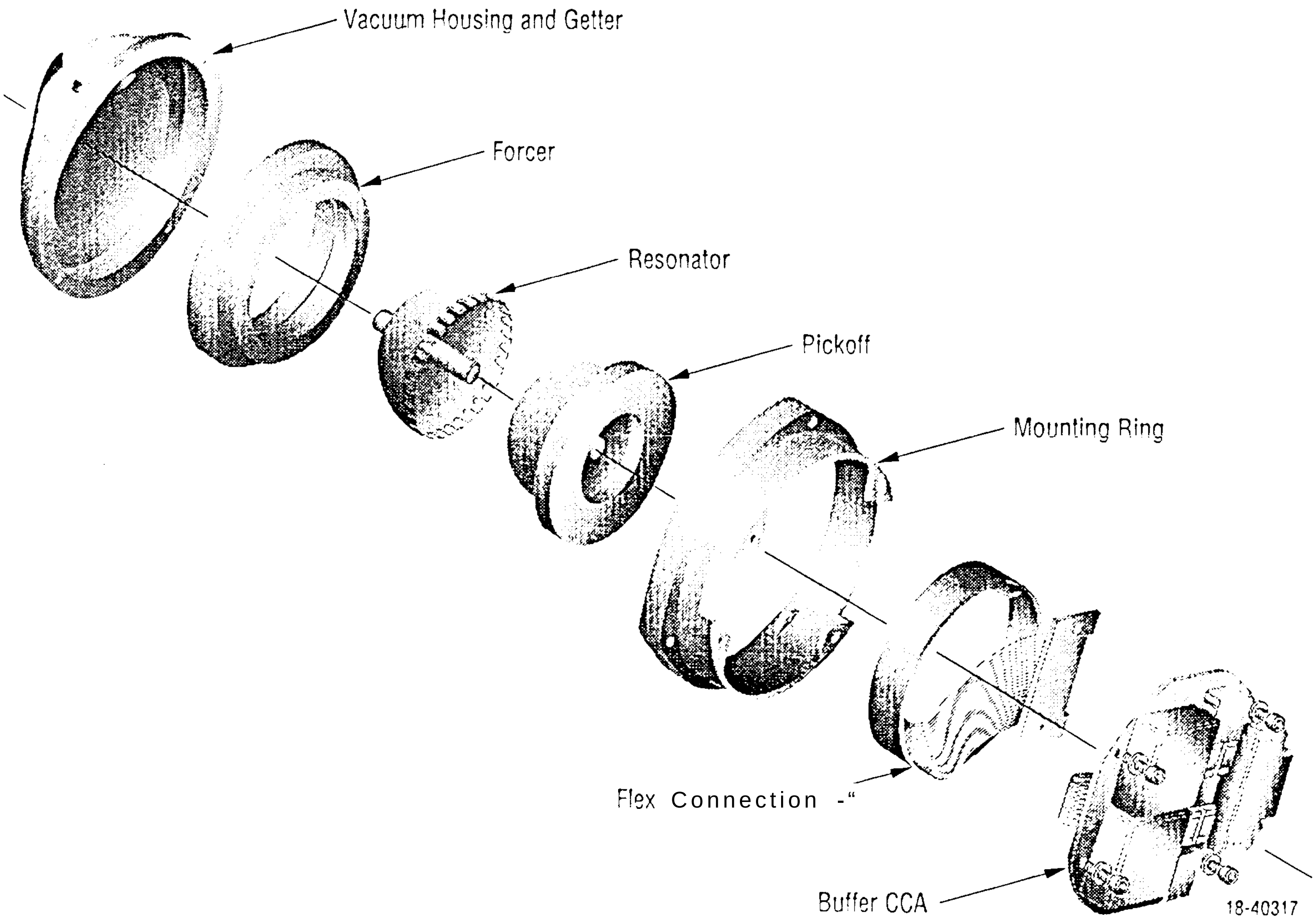
Modifications of SIRU for JPL

- Remove accelerometers
- Remove two external triax connectors
- Remove one Power Supply Module (PSM)
- Install RTIOU
- Redesign Power Supply to JPL requirements
- Add EMI shield between RTIOU and PSM
- Modify SEM for PROM instead of EEPROM
- Modify interconnect design

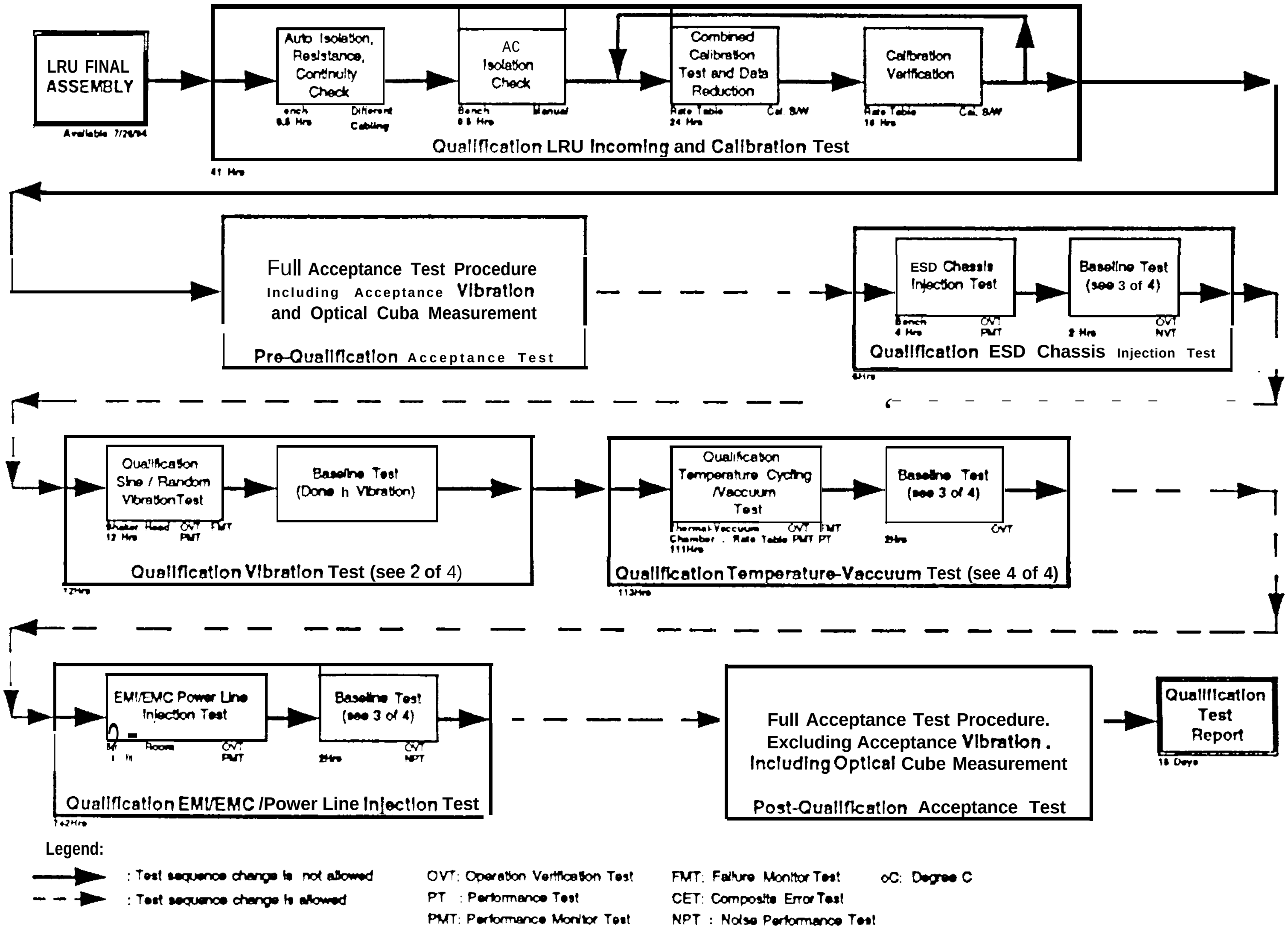
Cassini IRU Mechanization



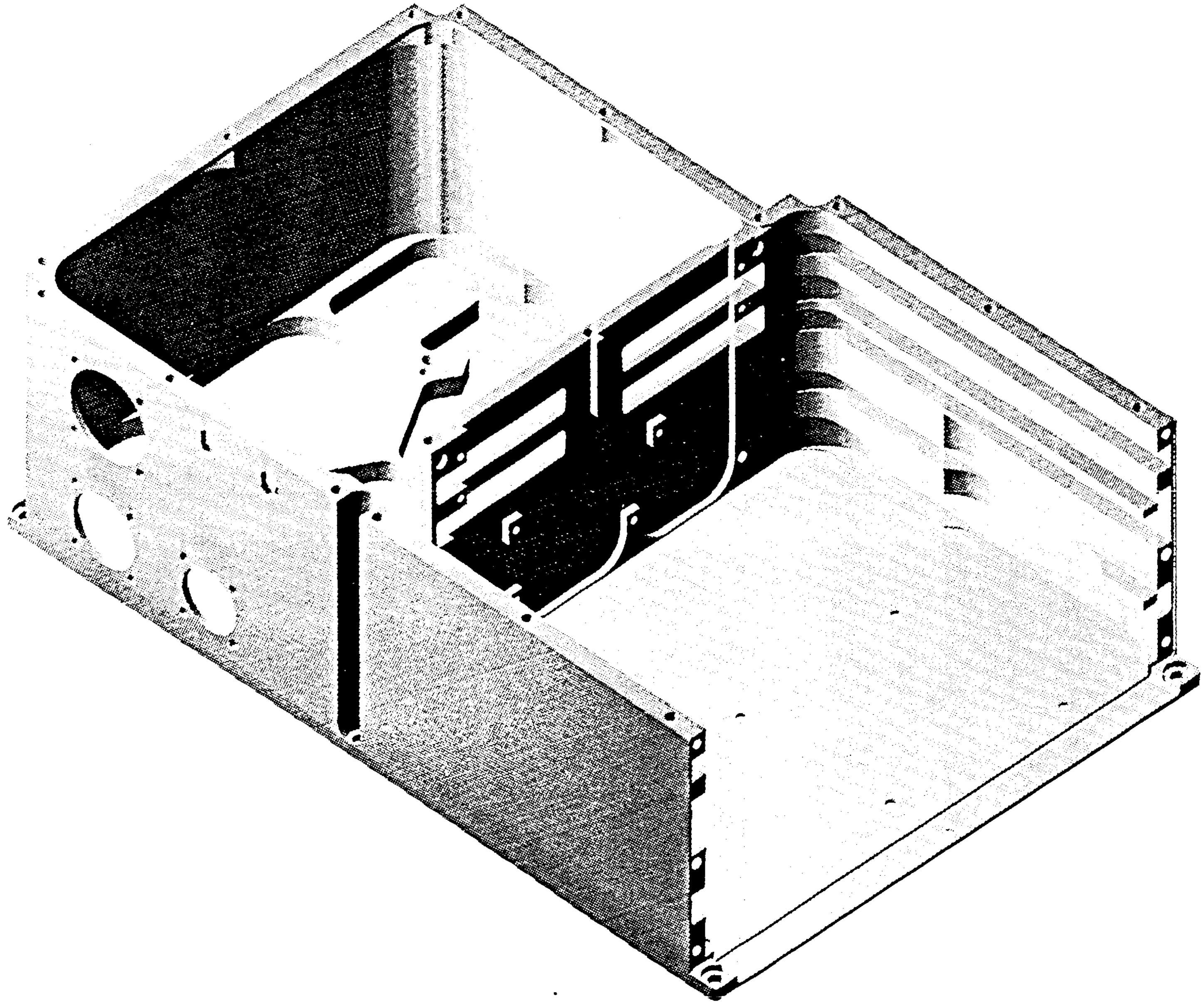
HRG – Exploded View



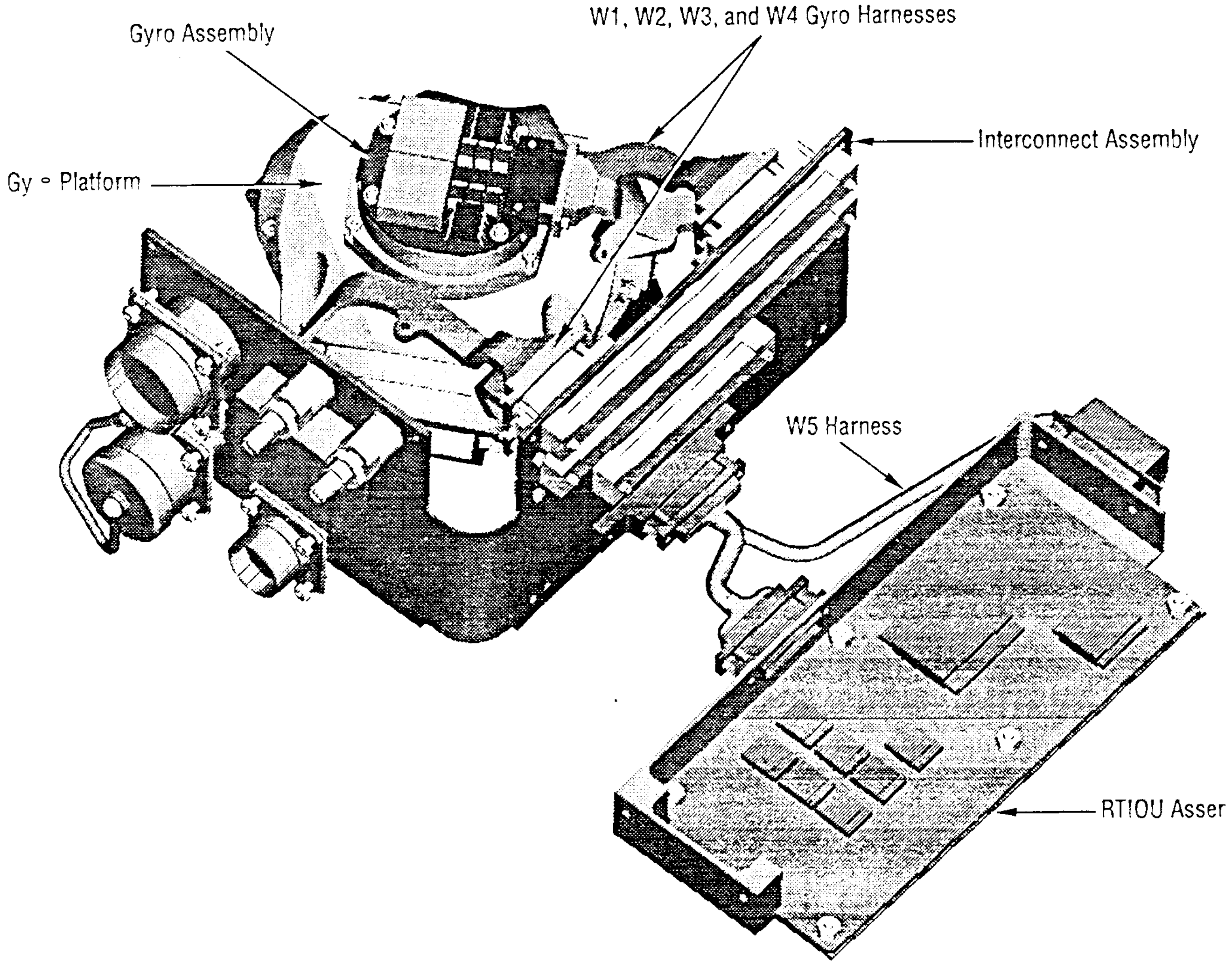
SIRU Qualification Test Sequence



Cassini IRU Enclosure



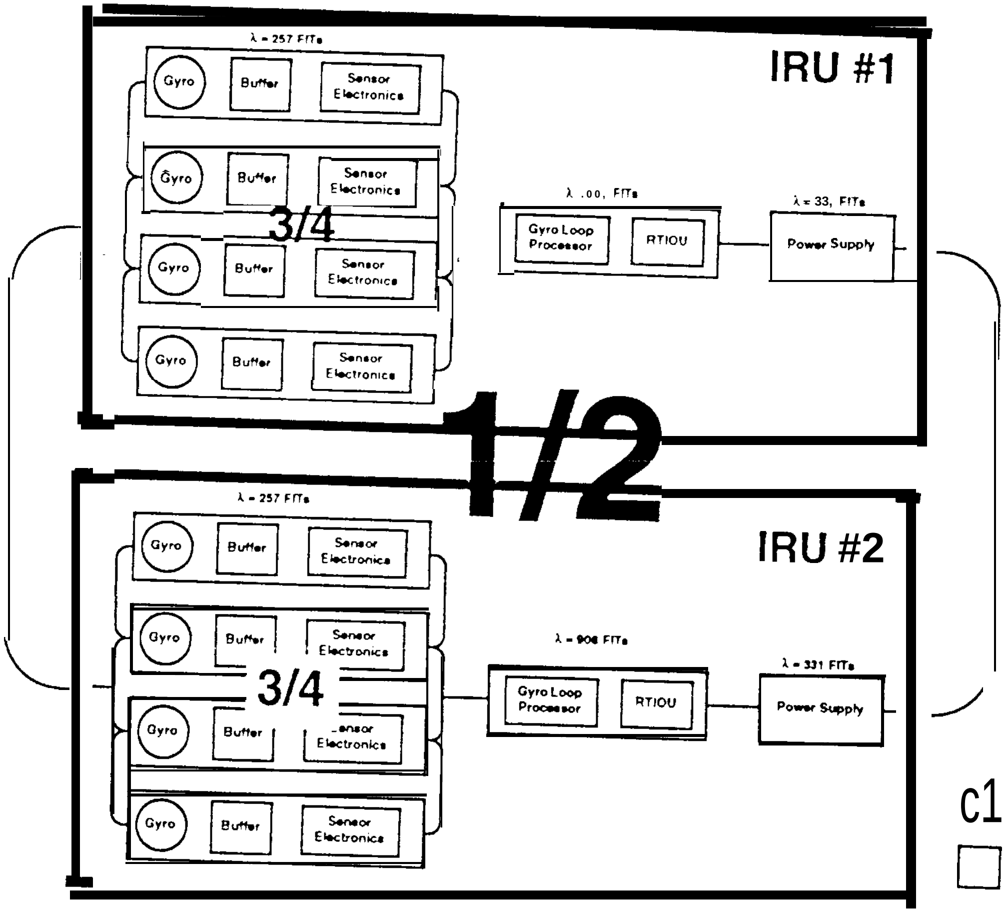
Interconnect Assembly and Harnessing



Weight Status Report
In Pounds

Subcontractor Part Number and Nomenclature	Current Status	Percent Estimated	Percent Calculated	Percent Actual
Enclosure	2.54		100	
Cover, Top	0.88			100
Cover, Access	0.36			100
Platform	0.38	100		
Interconnect Assembly	0.89	10		90
HRG (4)	1.50			100
Harnessing (5)	0.20	10	10	80
PS Module	1.15	2		98
SE Module (2)	1.42	2		98
Shield, SE Module	0.28			100
Shield, PS Module	0.35			100
Optical Cube	0.04			100
RTIOU	0.47			100
Hardware, Misc.	0.10	25	75	
Total SIRU Weight (lb)	10.36			

Cassini Shipset Reliability Block Diagram



c1 Active Unit (on)

Standby Unit (off)

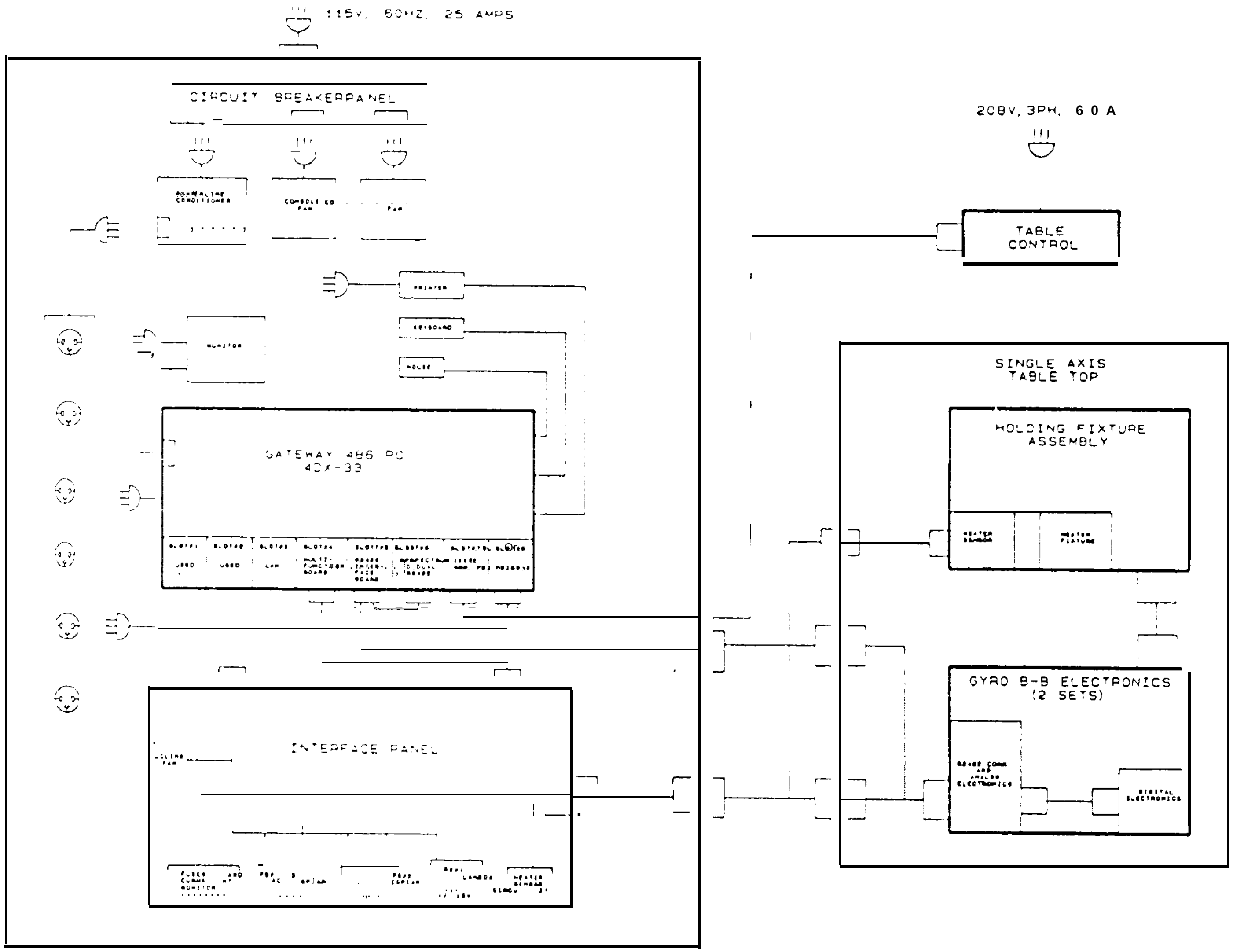
FITs = Failures Per Billlon Hours

Manual Card Test

SEM Tester

- RS-422 interface
- Dual 1553 interface
- Dual gyro interface
- Dual accelerometer interface
- Gyro I/O wraparound capability via breakout box
- Gyro test signals accessible via separate connector
- Selectable modes of operation for SHARC and GUPI
- Selectable 1553 terminal address
- Logic analyzer access to GSP/IOC/shared memory buses
- Power filtering/reg ulating/conversion circuitry
- Reset de bounce circuitry
- Fault signal indicator

130Y Gyro Test Station Block Diagram



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PSA Tester

Verify:

- Output voltage over outpu
  load ranges
- Power moding
- Relay switching
- Test point outputs
- Resistance and continuity ests
- Overload protection
- Test reset

Interface Protocol

RTIOU Commands

- Reset
- Read accumulated angle (via readusr)
- Read status (via readusr)
- Send a message (via writeusr)
  - Write absolute (download packet)
  - Start embedded processor

Read Accumulated Angle Command

Byte	Mnemonic	Packet Contents	Comments
1	Cmd Byte 1	IRUXADDR(H)	Destination=IRU (x=1 or 2)
2	Cmd Byte 2	0 0 0 X X 0 1 1	C:0=No Clamp A:0=Use Bus A O:0=No Override E:0=No Emergency R:1=AutoReply T:0=No Timetag
3	Ctrl Byte 1	BCIOUADR(H)	Source=BCIOU
4	Ctrl Byte 2	03(H)	Byte Count=03(H)
5	readusr	0 0 0 0 1 0 0 1	9 = # bytes in Gyro msg-1
6		0 0 0 1 0 0 0 0	
7	noOperation	1 1 0 0 0 0 0 0	Pad. Total # of Bytes must be even
8	checksum		Algorithm TBD

Word #	Description
1	Data Validity Word (modified)
2	Gyro A Integrated Angle Word
3	Gyro B Integrated Angle Word
4	Gyro C Integrated Angle Word
5	Gyro D Integrated Angle Word

Accumulated Angle Message

Read Status Command

Byte	Mnemonic	Packet Contents	Comments
1	Cmd Byte 1	IRUxADDR(H)	Destination=IRU (x=1 or 2)
2	Cmd Byte 2	0 0 0 X X 0 1 1	C:0=No Clamp A: O= Use Bus A O:0=No Override E:0=No Emergency R: I=AutoReply T:0=No Timetag
3	Ctrl Byte 1	BCIOUADR(H)	Source= BCIOU
4	Ctrl Byte 2	03(H)	Byte Count=03(H)
5	readusr	00001101	13 = # bytes in BIT msg-1
6		0 0 1 0 0 0 0 0	
7	cooperation	1 1 0 0 0 0 0 0	Pad. Total # of Bytes must be eve.
8	checksum		Algorithm TBD

Word #	Description
1	IRU **BIT** Status
2	IRU Gyro-A Detailed BIT Status
3	IRU Gyro B Detailed BIT Status
4	IRU Gvro C Detailed BIT Status
5	IRU Gyro D Detailed BIT Status
6	IRU CPU Detailed BIT Status
7	IRU Power Supply Detailed BIT Status

FC Download Procedure

- Command power subsystem to power up IRU
- Issue download messages
- If timeout, back up and retry
- Issue Start Embedded Processor message
- Read status and check Download Failure bit in CPU word
- Always check gyro validity bits before using gyro data

Mechanical Design

Key Requirements

Item	Requirement	Cassini IRU	Reference
Mass	<20 kg (44 lb)	4.70 kg (10.36 lb)	ES516188, 3,3.2.1
Structural Design	Per CAS-3-190	Complies	ES5 6188, 3.2.2.1
Vented Assemblies	Suitable to prevent damage due to pressure differences during rapid external change	Aperture area/volume = $\frac{0.075}{ft^3}$ ‘n’ (no less than 0.05 in^2)	ES5 6188, 3.2.2.4
Mounting Surface Flatness	≤1.27 ‘m (0.005 inch)	Drawing complies	ES5 6188, 3.3.2.4
Surface Finish of Mounting Surface (electrically conductive)	1.60 ^{6}m, or belter, unpainted electrically conductive (63 pin)	Drawing complies	ES5 6188,3 .3.7.2
Surface Finish Emissivity	≥0 95	Drawing complies	ES516188, 3.3.7.2
Structural Safety Factors (minimum)	≥1.25 (yield) structural elements 21.4 (ultimate) mass acceleration curves	Complies	ES516188, 3.3.6.1

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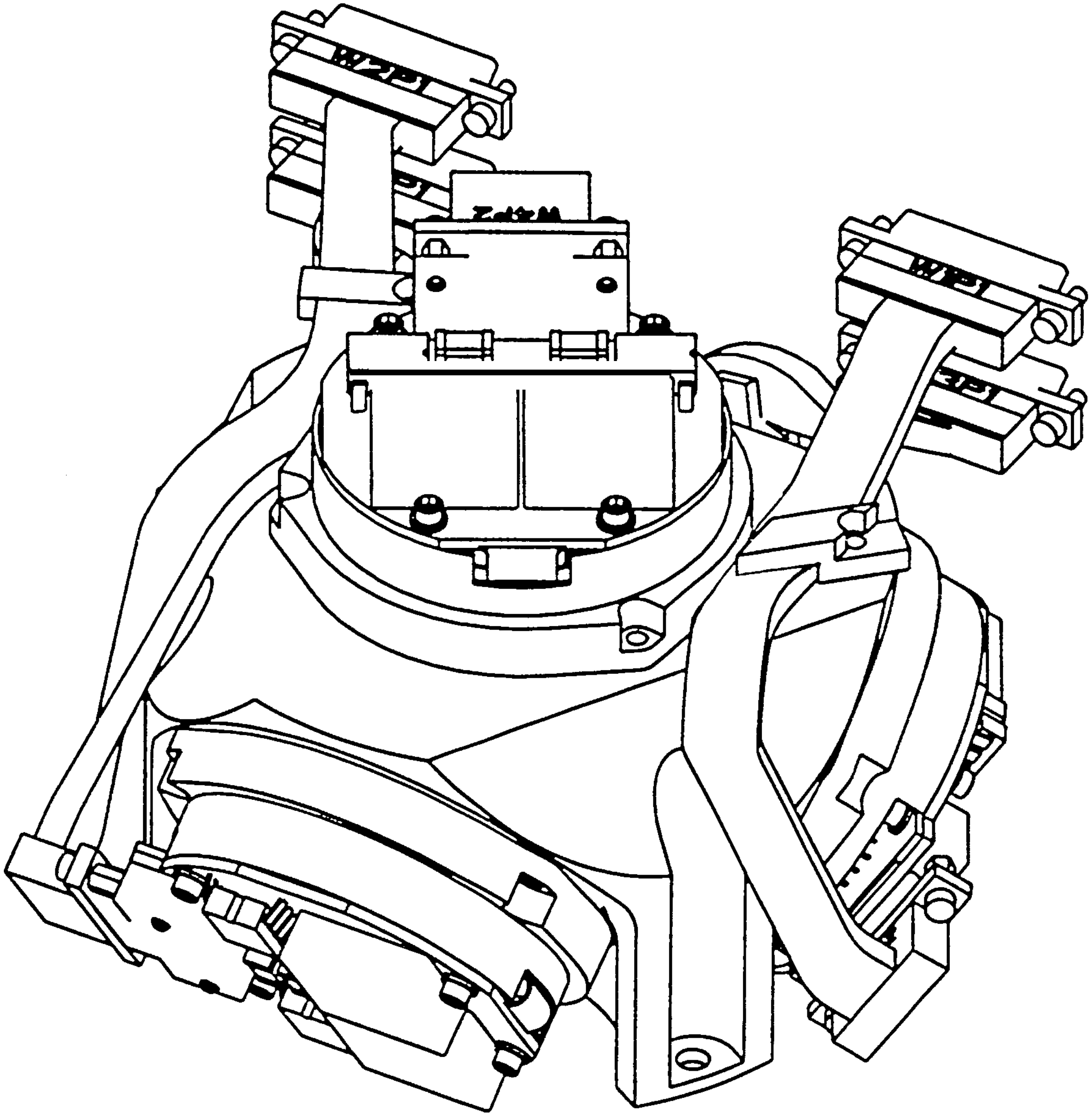
Harnesses



Enclosure Design

- One-piece housing; removable top cover and access cover
- Size (main body envelope): 11.90 **x 8.05 x 3.75** inches
- Material: aluminum alloy 6061 -T651, QQ-A-250/11
- Finish
  - Chemical film: MIL-C-5541, Class 3
  - Black anodize: MIL-A-8625, Type II, Class 2

Power Supply

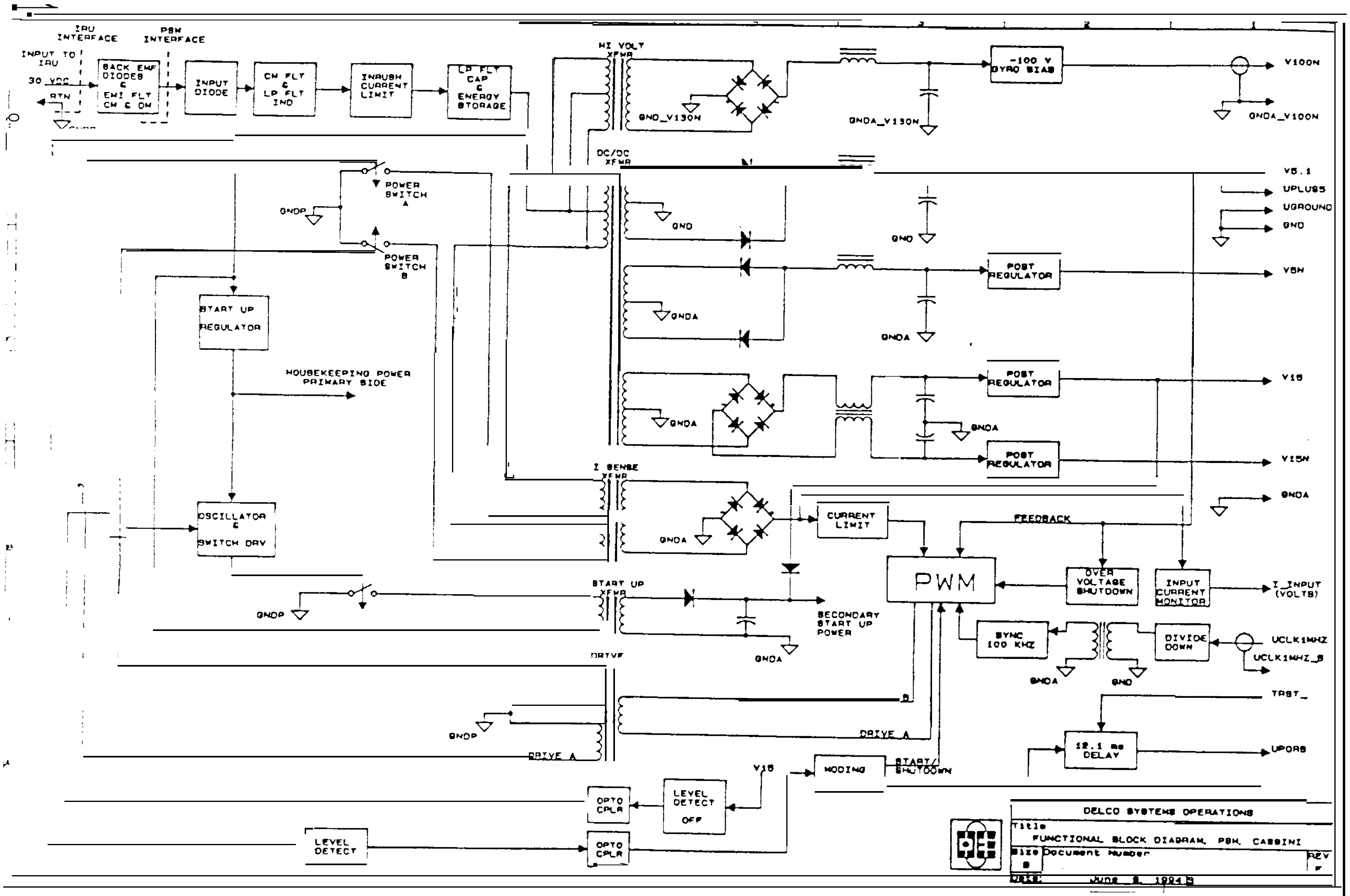
Key JPL Requirements

Requirements	Limits	Notes	Source
Input Power Consumption	26W nominal 39W maximum	Without redundant channels operating With all channels operating	ES516188, 3,2.3.4
Rate of Change of Input Current	75 mA/µs	For any time interval > 10 µs	ES516188, 3.2.3.7
Grounding and Isolation	N/A	Single point and isolated grounds	ES516188, 3.2.3,9
Input Power Bus S.S,	30V + 1.5, -2.89	In-specification steady state	CAS_3_250
Input Ripple Voltage	300 mV pp 1V pp	30 Hz< f<20kHz 20kHz < f < 50 MHz	ES516188, 3.2.3.11
Design Temperature	-5 to +45°C -30 to +75°C **-55** to +85°C	In specification performance Operational survival Nonoperational survival	ES516188, 3.3.7. ?
Back EMF Protection	>TBD µH load	Typical 75µH, single fault immune	CAS_3_250, 5.1.4.1.4
Load Input Impedance	$Z(f) = \frac{30}{I_{IN}} \sqrt{\frac{1+\left(f/4{,}000\right)^2}{1+\left(f/600\right)^2}}$	f <50 kHz	
Inrush Current Limit	2.25A	Single 3-A switch with 25% safety margin	CAS_3-250, 5.1.4.1.2
Synchronization	Multiples of 50 kHz	UCLK 1 MHZ signal should be used	CAS_3_250, 5.1.6

Key JPL Requirements (Continued)

Requirements	Limits	Notes	Source
RTIOU Power	5 Vdc at 0.43W minimum 0.98W nominal	5.1 ± 5%	ES515899, 8.1
UPORB	Active low (output)	User power-on reset	ES515899, 7.2
UCLK1MHZ	1 MHz (input)	User synchronization clock	ES515899, 8.1
Conducted Emission	7 mApp maximum	30 Hz < f < 50 MHz	699_261, 3.2.2,1
Common Mode Structure Current	60 dBµA maximum Decreasing at 6dB/oct 40 dBµA maximum	30 Hz < f < 200 kHz 200 kHz < f <2 MHz 2MHz<f<50 MHz	699_261 ,3,2.1,1
Conducted susceptibility	±14V ±21V	Differential mode Common mode	699_261, 3,2.1,1
Worst Case Analysis		Per JPL D_5703	699_221, 3,1.2
Stress Analysis		Per 51_A_04	699_221, 3.1.4.1
Power Supply Analysis		Per JPL D_5703	699_221 ,3.1.3

PSM Functional Block Diagram



Key Core SIRU Requirements

Requirements	Limits	Notes	Source
Output Voltages	–	–	SEM
Output Power	–		SEM
Overvoltage Protection	1 20%	Of nominal voltage	Internal
Overload Protection	130%	Of maximum output power	Internal
Soft Start	< 50 ms	–	Internal
PD_PS_	Active low	Power down moding signal	SEM
TRST_	Active low	Test reset	Test requirement

Power **Moding**

		Source
Power On		
• Turn-on threshold	30 Vdc FLT rising through -25 Vdc	Internal
• 30 Vdc FLT ↑ ?0 V5 ↑	Less than 50 ms	Internal
• V5 ↑ to PD_PS ↑	Concurrent	**SEM**
• PD_PS ↑ to UPORB ↑	12.1 ms minimum	ES515899, 7.2
Power Off		
• 30 Vdc FLT ↓ to PD_PS ↓	100 µs minimum	SEM
• PD_PS_ ↓ to UPORB ↓	100 µs minimum	SEM
• Shutdown	30 Vdc FLT falling through 15 Vdc	Internal

Input Voltage

Source: CAS-3-250, 5.1.1.1

	Maximum (Vdc)	Minimum (Vdc)
Used for PSM efficiency and thermal dissipation	30.25	27.86
In specification Steady State	31.50	26.62
In specification Transient $\leq 10\,\mu s$	35.20	22.88
Load fault Transient ≤ 5 ms	35.20	22.88

Output Voltage Characteristics

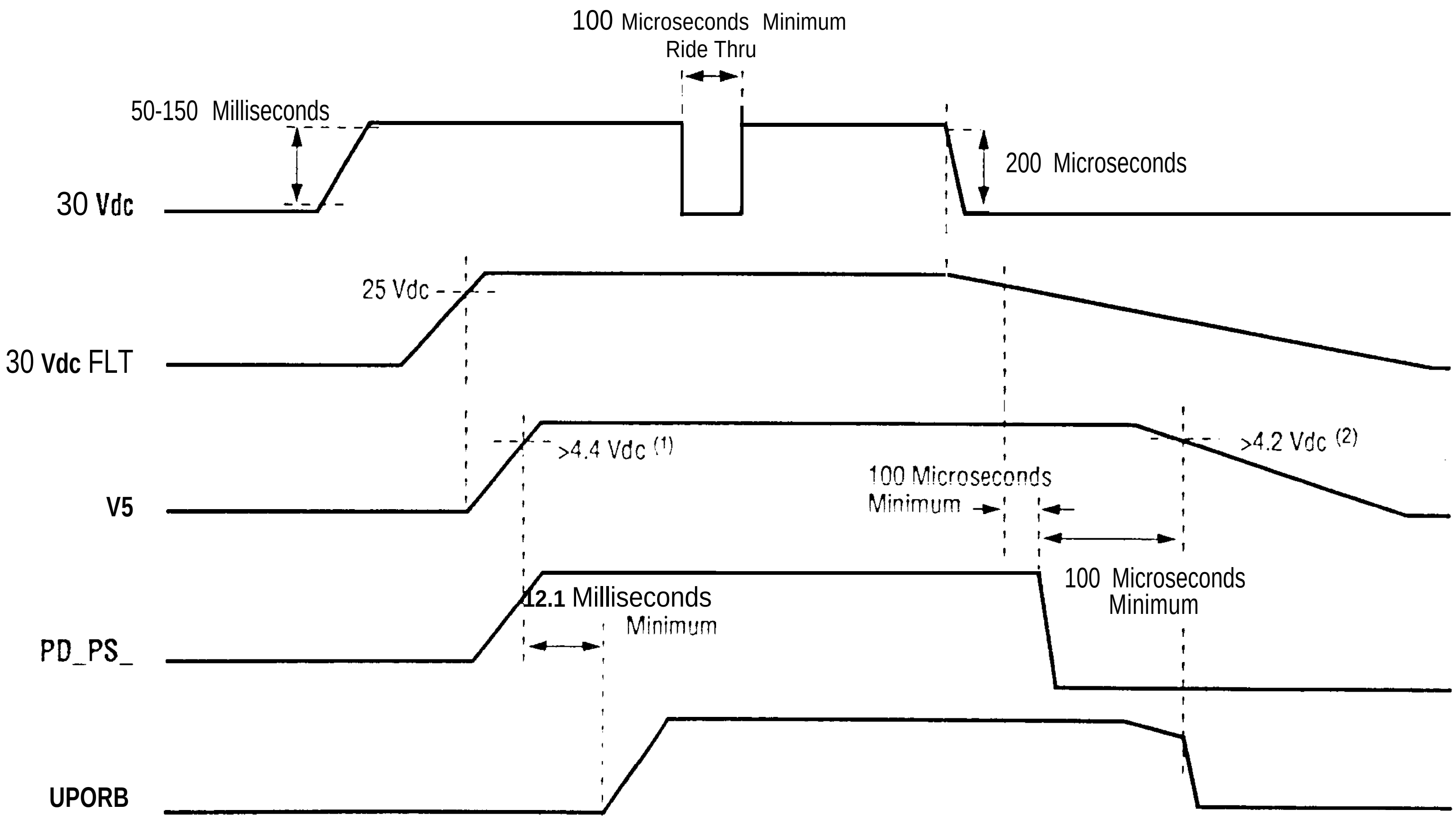
Source: Core SIRU

Output Voltage	Minimum (W)	Nominal (W)	Maximum (W)	Tolerance (±%)
+5.1 (1)	3.18	3.96	5.03 (2)	5
-5	0.54	0.60	0.69	10
+15	4.37	4.86	5.58	7
-15	3.73	4.15	4.77	7
-100	Capacitive	Capacitive	Capacitive	3

(1) RTIOU power is included

(2) Does not include 3.84W maximum transient fault load condition for RTIOU. However, the PSM can accommodate this transient load to enhance RTIOU fault recovery.

Power Moding Diagram



NOTES:
1 UPORB is unassorted when V 5 rises to within 4.4 – 4.6 Vdc
2, UPORB is asserted when V5 falls to within V5 maximum -42 Vdc

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Sensor Performance

Requirements Flowdown

The system performance specifications are flowed down to the individual instrument and electronics parameters with error budgets that partition the total error according to the expected characteristics of each parameter. Vendor specifications and some in-house measurements are used to predict the variations of each parameter. The output error model is used to relate the budget figures to specific mechanical or electronics design elements. Budgets and corresponding specifications are given for both short-term and long-term environments. The short-term figures reflect errors during 16 hour periods of moderate thermal variation (+-1 5 C such as encountered in Earth orbit) while the long-term figures reflect errors over the whole mission including full thermal environments (-34 to +71 C) and accumulated radiation dose.

System performance specifications

Measurements of actual system performance

instrument build Specifications and Previous HRG measurements

Electronics requirements

Electronics and instrument error budgets

Component Specifications from data book and worst-case guidelines

Instrument requirements

Detailed equations of motion for HRG

Bias and scale factor error model

Lumped parameter model for analog electronics errors

Status of Error Budget and Worst-case Analysis

Preliminary error budgets for scale factor and bias performance were presented at PDR. A few of the allocations in these error budgets have been updated since PDR to reflect our present knowledge of the component-level characteristics. A summary of the changes to the error budget is as follows:

- Net increase in the short-term scale factor error budget from 93 to 217 PPM and a net decrease in the long-term error budget from 2088 to 1040 PPM
  - More rigorous accounting of effective resonator voltage caused slight increase in short and long term budget figures. (See row 1 in table 1, 50/200 increased to 60/250)
  - Capacitance measurements and inertial tests reveal hysteretic changes in the 130Y gyro forcer gap. Calibration models are expected to capture the majority of the effects since two of the reference signals will track the changes in the gap. (See row 3 in table 1, 50/400 increased to 200/700)
  - More data from vendor reveals that worst-case DAC scale factor changes due to radiation are much smaller than originally estimated. The large radiation effects were due to changes in the DAC's internal voltage reference which is not used in SIRU. (See row 8 in table 1, 25/2000 decreased to 25/600)
- No change in bias error budget

The worst-case analysis that is required to validate the long-term specifications in the error budgets is scheduled for completion after CDR.

Scale Factor Error Budget

	Parameter	Budget, 3σ PPM 16 hr. (15 yr.)	Specification
1	V_B $V_{R,dc}$ $V_{x,dc}$	60 (250)	$\delta V_B < 2.5\ (10.0)$ mV $\delta V_{R,dc} < 2.5\ (10.0)$ mV $\delta V_{x,dc} < 2.5\ (10.0)$ mV
2	ω	10 (10)	$\delta\omega < 10\ (10)$ PPM
3	d_f	200 (700)	$\delta d_f < 100\ (350)$ PPM
4	d_p	25 (200)	$\delta d_p < 25\ (200)$ PPM
5	C_s	25 (200)	$\delta C_s / C_0 < 25\ (200)$ PPM
6	G_{ap}	25 (200)	$\delta G_{ap} < 25\ (200)$ PPM
7	V_0	25 (200)	$\delta V_0 < 0.028\ (0.23)$ mV
8	G_{rd}	25 (600)	$\delta G_{rd} < 25\ (600)$ PPM
9	V_{sx} ϕ_r	10 (10)	$\delta V_{sx} < 10$ mV $\delta\phi_r < 0.0017$ rad
10	β_{ra} ϕ_r	10 (10)	$\beta_{ra} < 590$ PPM $\delta\phi_r < 0.0017$ rad
11	κ	10 (10)	$\delta\kappa < 1\ V/\mu s$ $(\kappa \geq 10\ V/\mu s)$
12	β_{rn} Δ_{OLQ}	10 (10)	$\beta_{rn} < 740$ PPM $\Delta_{OLQ} < 0.0006$ rad/sec

Table 1 -- Scale factor error budget

The scale factor error mechanisms are briefly described as follows:

1-8: A number of parameters appear in the nominal scale factor. Fractional errors in these terms will cause scale factor errors directly. In the case of squared terms (1 and 3), the parameter errors have a x2 effect.

9: A combination of circuit offset and phase error is specified so that this error source is limited to 10 PPM.

10: A combination of phase error and forcer-pickoff coupling is specified so that this error source is limited to 10 PPM.

11: Scale factor errors resulting from variation in the DAC slew rate are specified to meet a 10 PPM budget.

12: Errors due to residual open-loop quadrature and forcer-pickoff coupling are specified to meet a 10 PPM budget.

Bias Error Budget

	Parameter	Budget, 3σ deg/hr 16 hr. (15 yr.)	Specification
1	$\Delta_{1/\tau,s}$	0.006 (0.1)	$\delta\Delta_{1/\tau,s} < 35\ (580)\cdot 10^{-9}$ 1/sec
2	$\Delta_{\omega,c}$ V_{sy} V_{OLQ}	0.006 (0.2)	$\delta\Delta_{\omega,c} < 0.00015$ rad/sec δV_{sy} 0.075 (2.5) mV δV_{OLQ} 11 (380) mV
3	$\Delta_{4d,s}$ V_{PARA}	0.006 (0.2)	$\Delta_{4d,s} < 0.005$ $\delta V_{PARA} < 11\ (360)$ mV
4	V_{cy} $\Delta_{1/\tau,c}$	0.006 (0.01)	$\delta V_{cy} < 3\ (5)$ mV $\Delta_{1/\tau,c} < 1\cdot 10^{-5}$ 1/sec
5	β_{an} $\Delta_{1/\tau,c}$	0.006 (0.01)	$\delta\beta_{an} < 210\ (350)$ PPM $\delta\Delta_{1/\tau,c} < 9\ (15)\cdot 10^{-7}$ 1/sec $\Delta_{1/\tau,c} < 1\cdot 10^{-5}$ 1/sec

Table 2 -- Bias error budget table

The bias error mechanisms are briefly described as follows:

1: The intrinsic mechanical (damping asymmetry) bias of the HRG is specified according to experience and is allocated 0.1 deg/hr long-term.

2: Bias resulting from open-loop quadrature compensation errors is specified according to expected radiation effects on components and is allocated 0.2 deg/hr.

3: Bias from parametric forcer asymmetry is limited to 0.2 deg/hr long-term through requirements on gap run-out and circuit errors.

4: Combination of rate loop offset and damping term is specified such that this bias is limited to less 0.01 deg/hr.

5: Combination of coupling term and damping term is specified such that this bias is limited to 0.01 deg/hr.

Error Budgets on Spacecraft Axes

Cassini performance specifications are given in terms of errors about the spacecraft axes. The error budgets and margins must be restated with consideration given to the mapping of gyro input axis errors to IMU box axes. To do this, we use a covariance matrix generated from the directional cosines for the SIRU instrument configuration. The rows of the directional cosine matrix are selectively zeroed to characterize different instrument configurations. The directional cosine matrix is shown along with the five covariance matrices corresponding to each of the three- and four-gyro configurations. The diagonals of the covariance matrices show the mapping of the gyro axis variances to the box axes variances. The square-root of the maximum diagonal element in all of these matrices yields the factor that must be applied to the gyro 1A budgets in order to approximate the statistics of the transformed outputs in worst-case. The worst-case configuration is B,C, D and dictates a factor of 2.23 reduction in the allowable errors about the gyro axes.

$$\Gamma = C_B^G = \begin{bmatrix} 0 & -\sqrt{\frac{2}{3}} & -\frac{1}{\sqrt{3}} \\ \frac{\sqrt{2}}{2} & \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} \\ -\frac{\sqrt{2}}{2} & \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} \\ 0 & 0 & 1 \end{bmatrix}$$

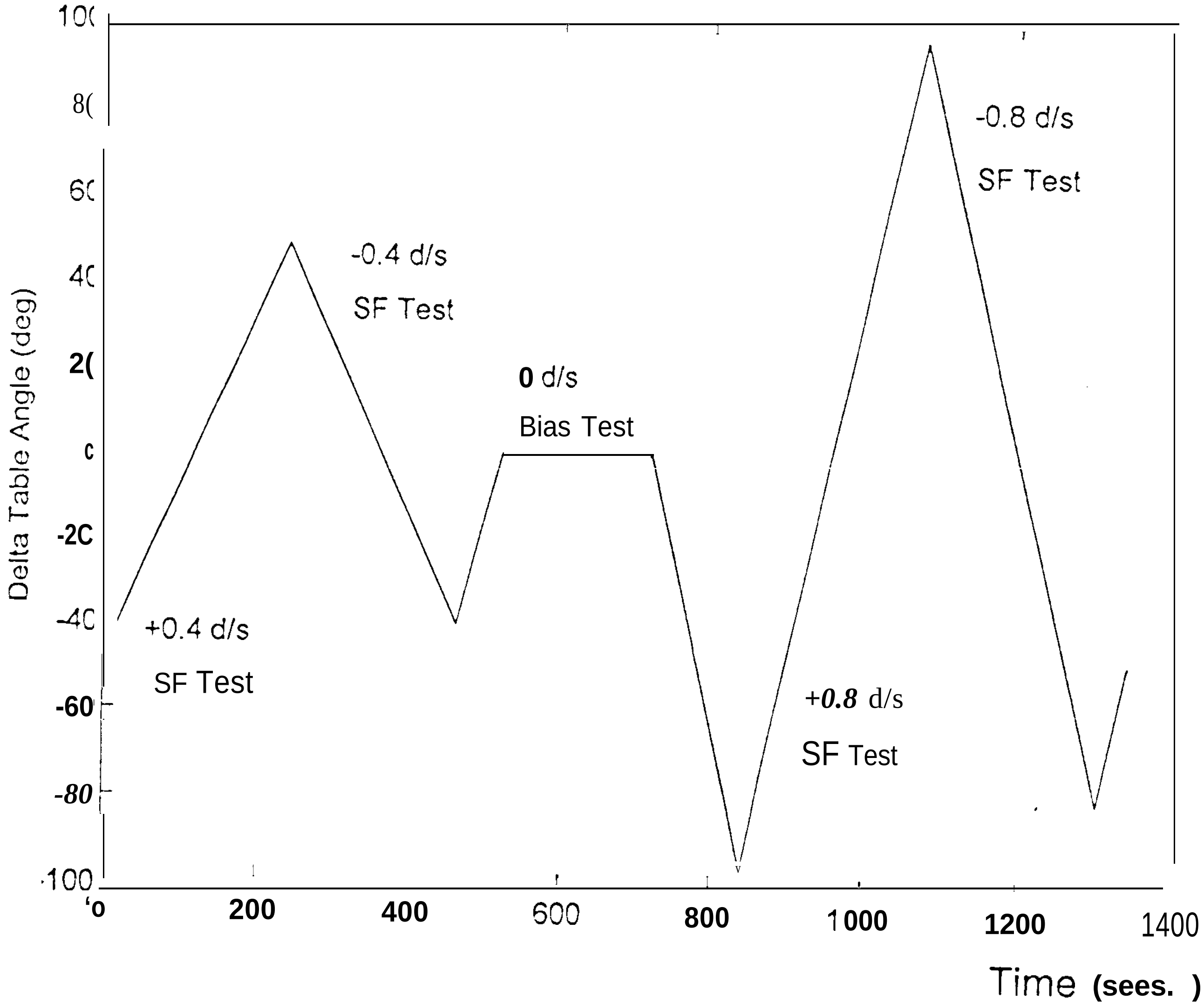
$$\left(\Gamma^T\Gamma\right)^{-1} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0.5 \end{bmatrix}}_{A\ BCD}, \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & 5 & 1.41 \\ 0 & 1.41 & 1 \end{bmatrix}}_{BCD}, \underbrace{\begin{bmatrix} 4 & 1.73 & -1.23 \\ 1.73 & 2 & -0.71 \\ -1.23 & -0.71 & 1 \end{bmatrix}}_{ACD}, \underbrace{\begin{bmatrix} 4 & -1.73 & 1.23 \\ -1.73 & 2 & -0.71 \\ 1.23 & -0.71 & 1 \end{bmatrix}}_{ABD}, \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{ABC}$$

Error Budgets on Spacecraft Axes

The table below summarizes the requirements, budgets, and margins for the important gyro performance characteristics. .

Parameter	Requirements (box axes)	Requirements (gyro axes)	Budgeted Performance	Margin (RSS)
Scale factor error (long-term)	0.25 % 3-σ	**0.112**	**0.104**	**0.042**
Scale factor accuracy (30 *days)*	0.05 % 3-σ	0.0224	0.0217	0.005
Bias (long term)	30 deg/hr 3-σ	13.5	0.3	13.497
Bias stability (8 hours)	1 deg/hr 3-σ	0.448	0.014	0.4479

Bias/SF Test Profile



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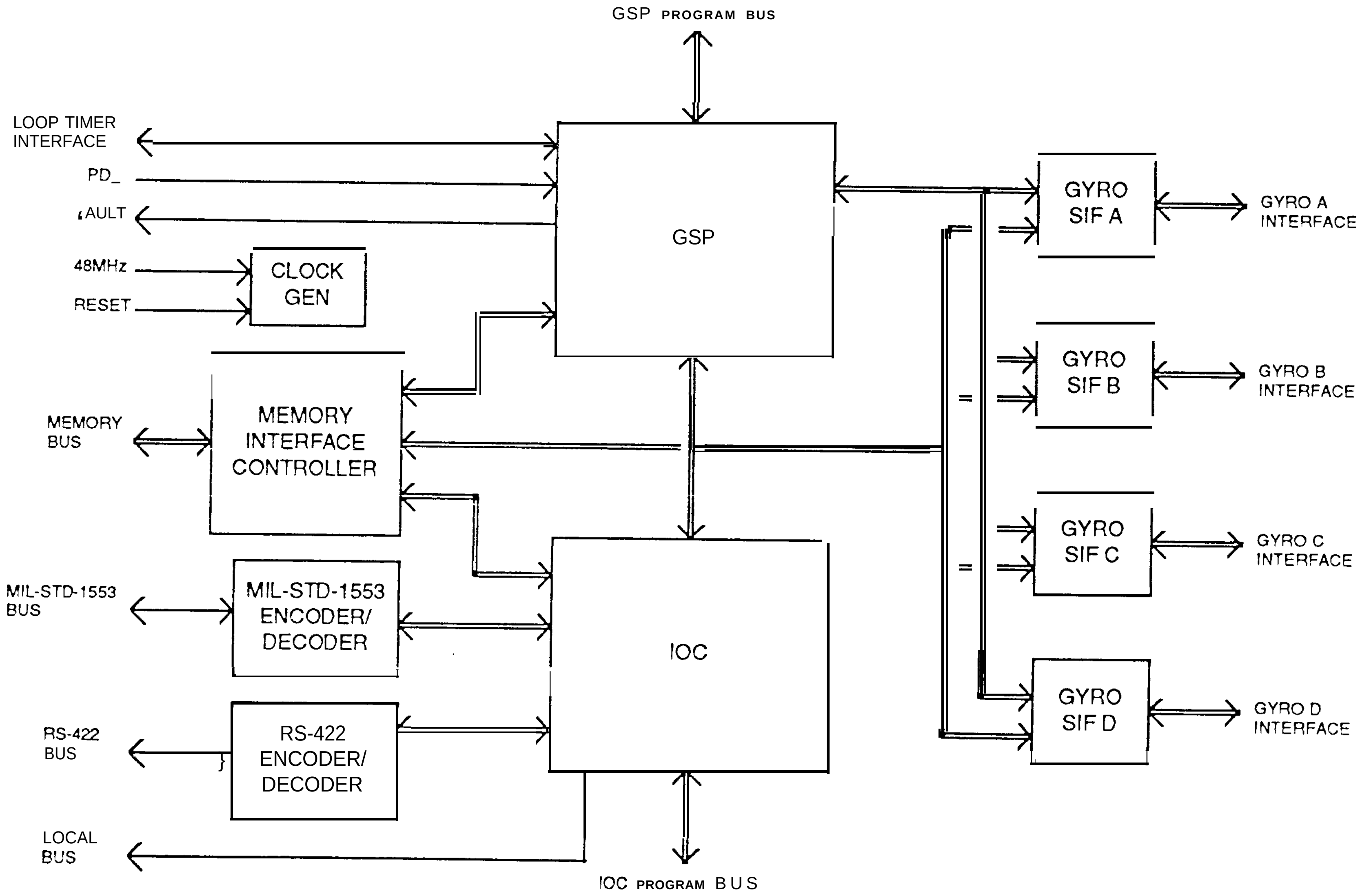
SHARC Block Diagram



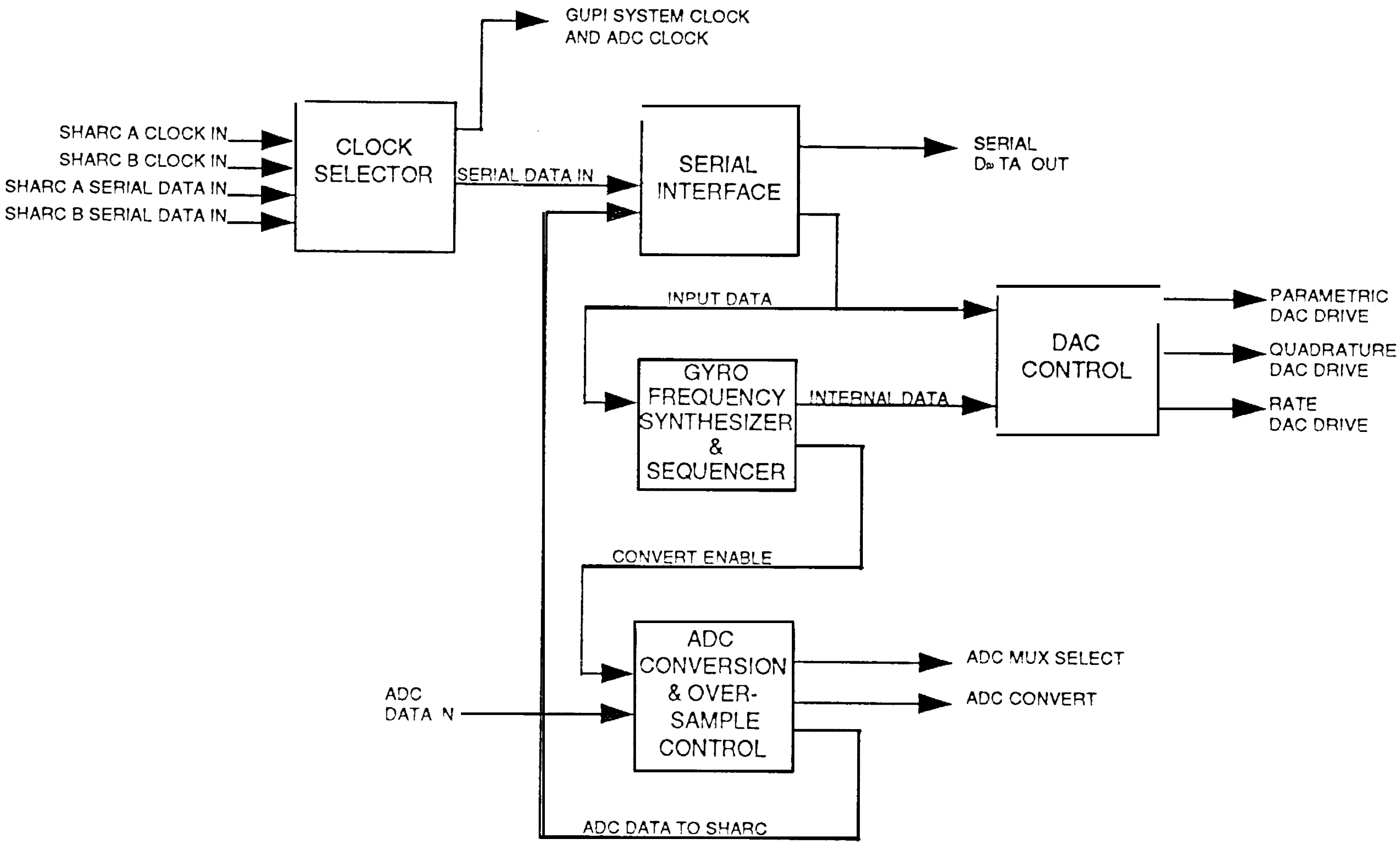
SHARC Features

- Gyro Signal Processor (GSP)
- Input/Output Controller (IOC)
- Memory Interface
- RS-422 Bus Interface
- Four Serial Interfaces to GUPI
- Programmable I/O

Summary of **SHARC ASIC** Update

- Serial interface DMA address counter/interrupts
- GSP code parity error response
  - Modified to ensure error detection and correction
- Memory interface
  - Modified EEPROM/PROM cycle for flexibility
- Shutdown serial interfaces on GSPFAULT
- GSP minor instruction fixes included
- IOC
  - DMA complete flag changed for EEPROM/PROM cycle flexibility
- Testability enhancements

GUPI Block Diagram



Chip Test Fault Coverage

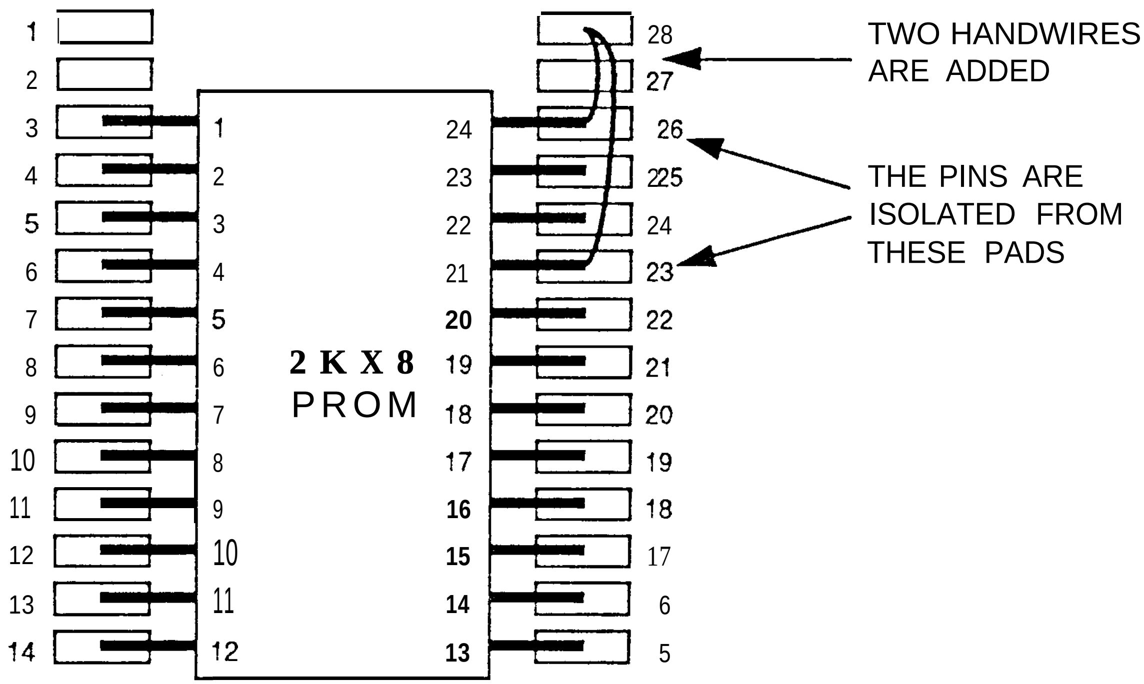
GUPI

- 2[illegible] functional vectors
- 387 scan vectors
- 00 percent toggle coverage
- >98 percent fault coverage

SHARC

- 28[illegible]0 functional vectors
- Scan vector development in process. Current status is:
  - TBD scan vectors
  - TBD percent fault coverage

Installation of the PROM's on EEPROM Footprints



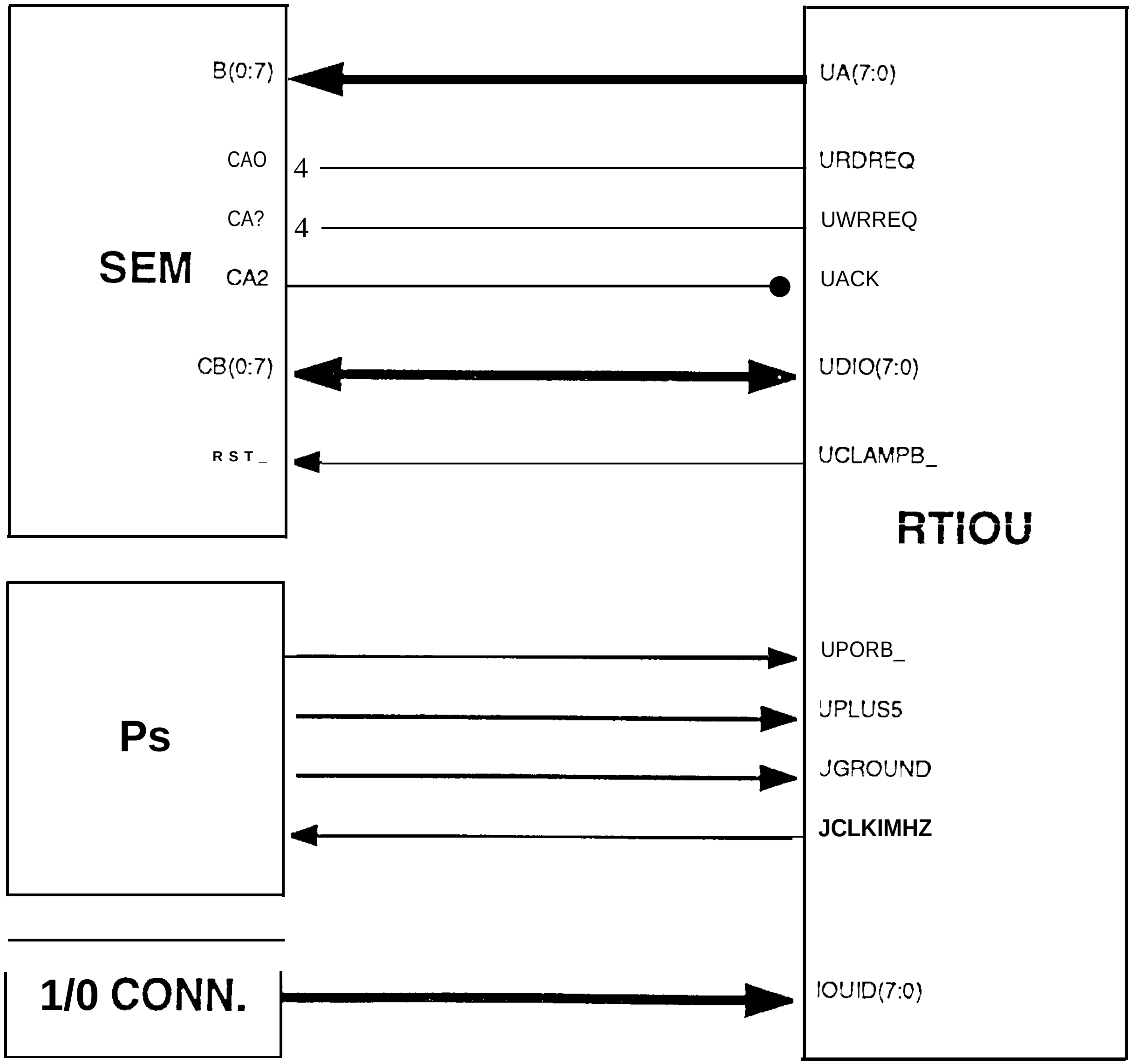
EEPROM to PROM Change

- 2k x 8 PROM fits in the 32k x 8 EEPROM footprint with two handwires per part
- SHARC2 is compatible with timing requirements of PROM
- Harris rad-hard 2k x 8 PROM is on JPL's approved parts list
- **We** will download over AACS Bus for GSP code

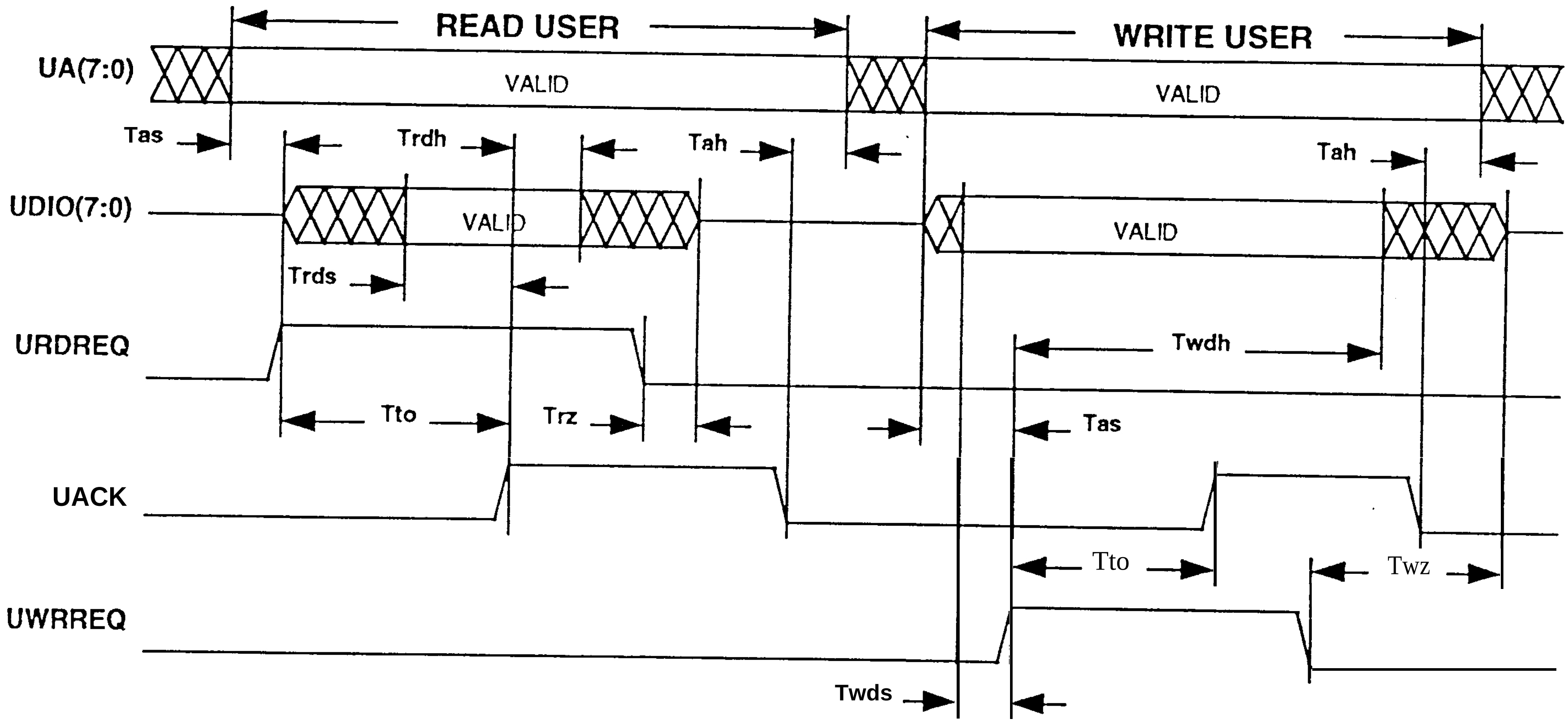
RTIOU Requirements

- Interface to user electronics as to a 256 x 8 “pseudo RAM”
- User acknowledge “handshake” with each 8-bit transfer
- At least one 8-bit address to “no respond” for test purposes
- 8-bit IOUID routed to I/O connector
- Power-on reset to RTIOU
- UCLAMPB_must hold user electronics in reset
- 1-MHz square wave signal to power supply for sync

Interface with RTIOU



RTIOU interface Timing



Tto = 500 us max

Trds = 500 ns min

Trdh = 50 ns min

Trz = 1 us max

Critical Timing Parameters of User Electronics Response

Digital Design Analysis

Worst-case Timing Analysis

- Performed for SHARC and GUPI ASIC designs
- Performed for SEM CCA digital design
- Positive margins in all cases
- Setup time conditions
  - 4.5V, 125°C, worst case processing, pre-rad
- Hold time conditions
  - 5.5V, -55°C, best case processing, post-rad

Digital Design Analysis (Continued)

System Level Simulation

- Model included
  - SHARC and GUPI gate level models
  - Memory, gyro, analog, RS-422, and MIL-STD-1553 behavior models
  - Simulated inputs for rate, temp, and quad
- Environment included
  - Zycad hardware accelerator
  - HP/Apollo workstation
  - GSP and IOC assemblers
  - Logging of RS-422 messages and gyro response
- Simulation included
  - GSP and IOC chip tests
  - IOC OFP development
  - RS-422 messages
  - Memory scrub, sleep, and other routines
  - GSP OFP
  - RS-422 and MIL-STD-I 553 communication
  - Gyro control using GUPI

IOC OFP Firmware

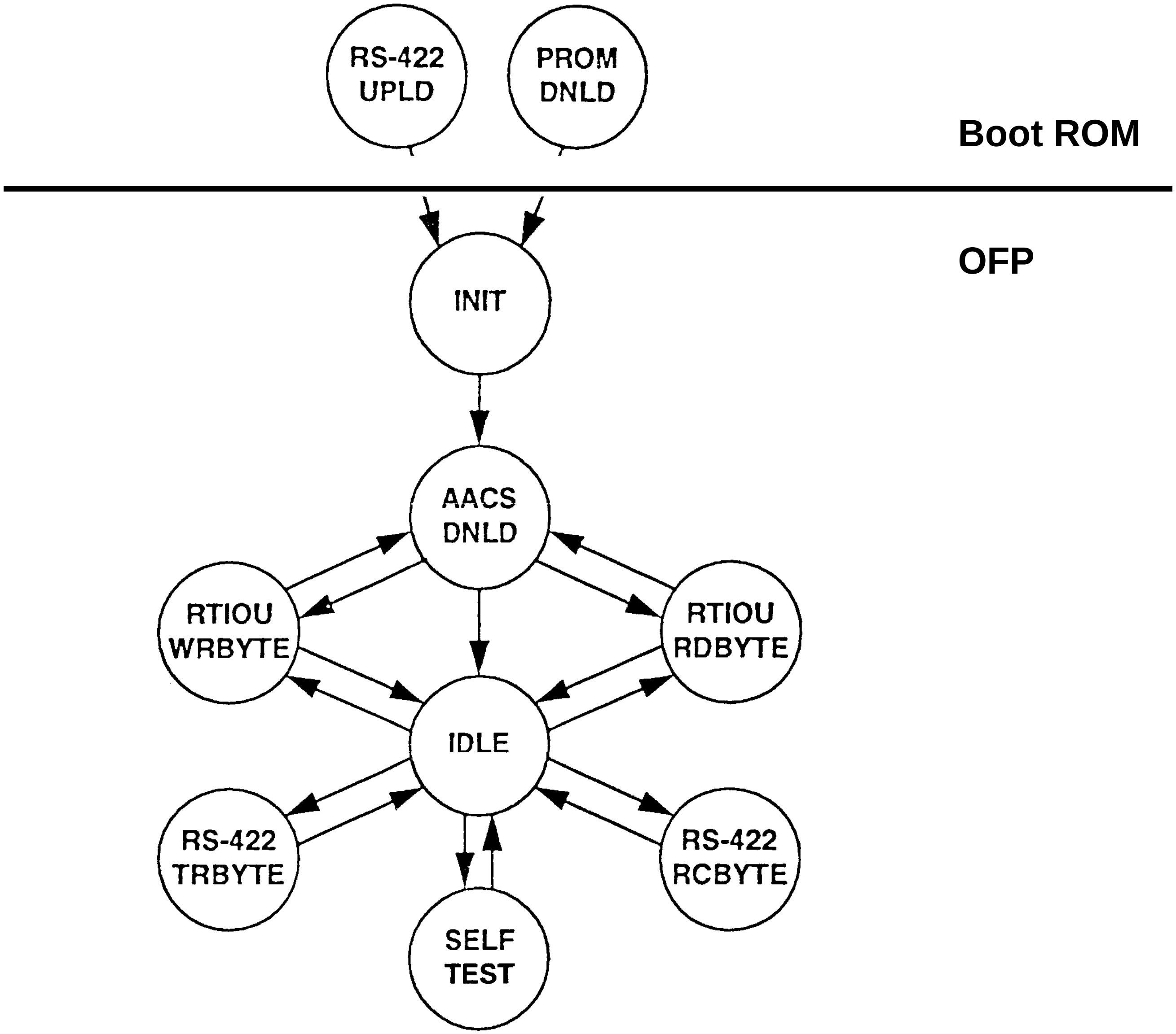
Requirements

- Cassini electrical interface control document
- RS-422 Programming Manual EE-2137
- Cassini Flight Equipment AACS RTIOU Specification ES51 5899

Components

- RTIOU interface
- RS-422 interface
- AACS bus download of GSP code
- Self-test

IOC Firmware Design



IOC Firmware Components

RS-422 UPLD

- Provides capability to load RAM from test equipment

PROM DNLD

- Transfers IOC OFP from PROM to IOC code RAM
- Calculates checksum
- Retry on error condition

INIT

- Initialize IOC internal configuration registers

IOC Firmware Components (Continued)

AACS DNLD

- Performs download of GSP code from AACS bus (RTIOU)

IDLE

- Polls RT OU interface for receive/transmit processing
- Polls RS-422 interface for receive/transmit processing
- Initiates background self-test

SELF-TEST

- Performs background self-test of IOC

IOC Firmware Components (Continued)

- RTIOU WRBYTE
  - Receive written byte from RTIOU and DMA to data memory
- RTIOU RDBYTE
  - DMA byte from data memory and output to RTIOU
- RS-422 RCBYTE
  - Receive one byte of RS-422 data and manage state
- RS-422 TRBYTE
  - Transmit one byte of RS-422 data and manage state

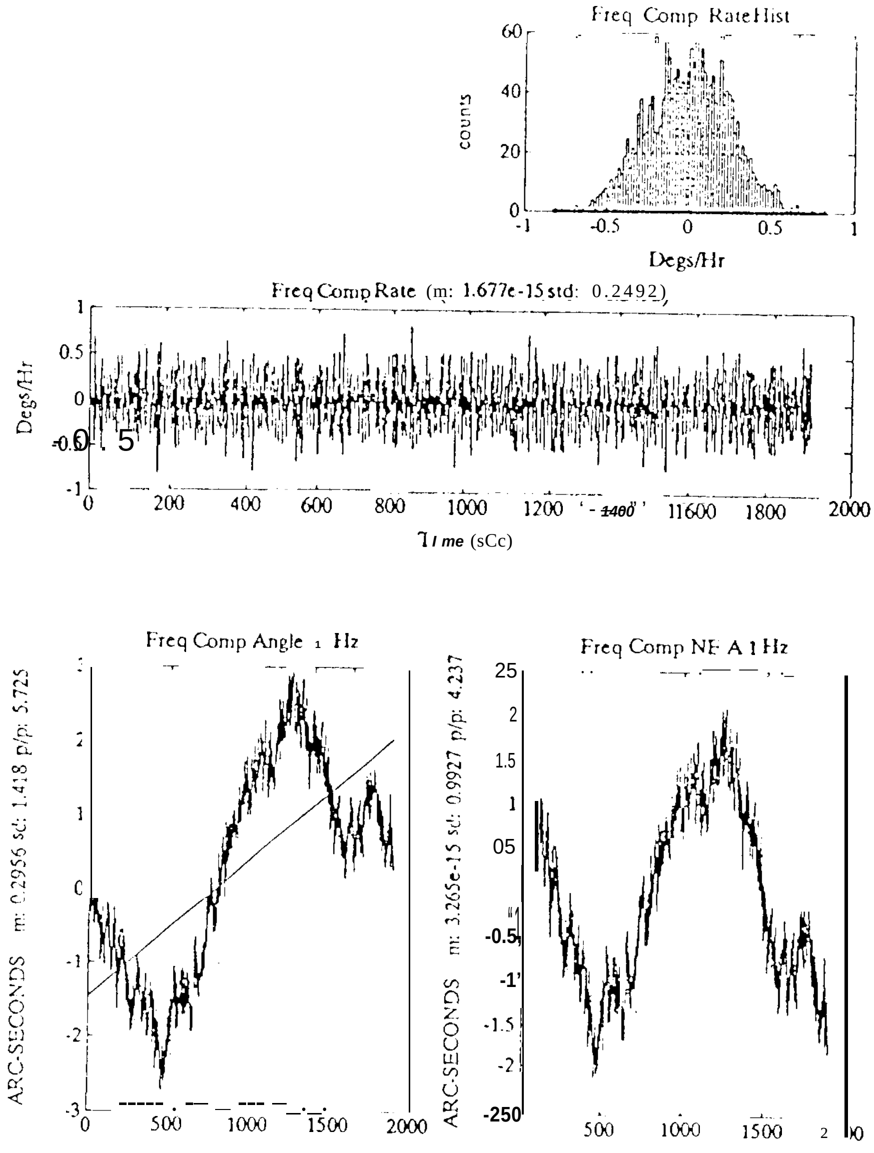
Noise Equivalent Angle Test

- Test run at constant temperature immediately after a 16 hour Scale factor and Bias test.

SIRU #: EDU3

Date	Gyro	SIN	pk/$\frac{pk}{sec}$	Comments
9 June	A B C D	16 15 13 12	3.7 5.9 4.5 3.8	22" C temp.
10 June	A B c D	16 15 13 12	4.34 4.71 3.27 " 5.89	22" C temp.
11 June	A B c D	16 15 13 12	4.93 4.86 4.70 3.65	42° C temp.

Sample NEA Test



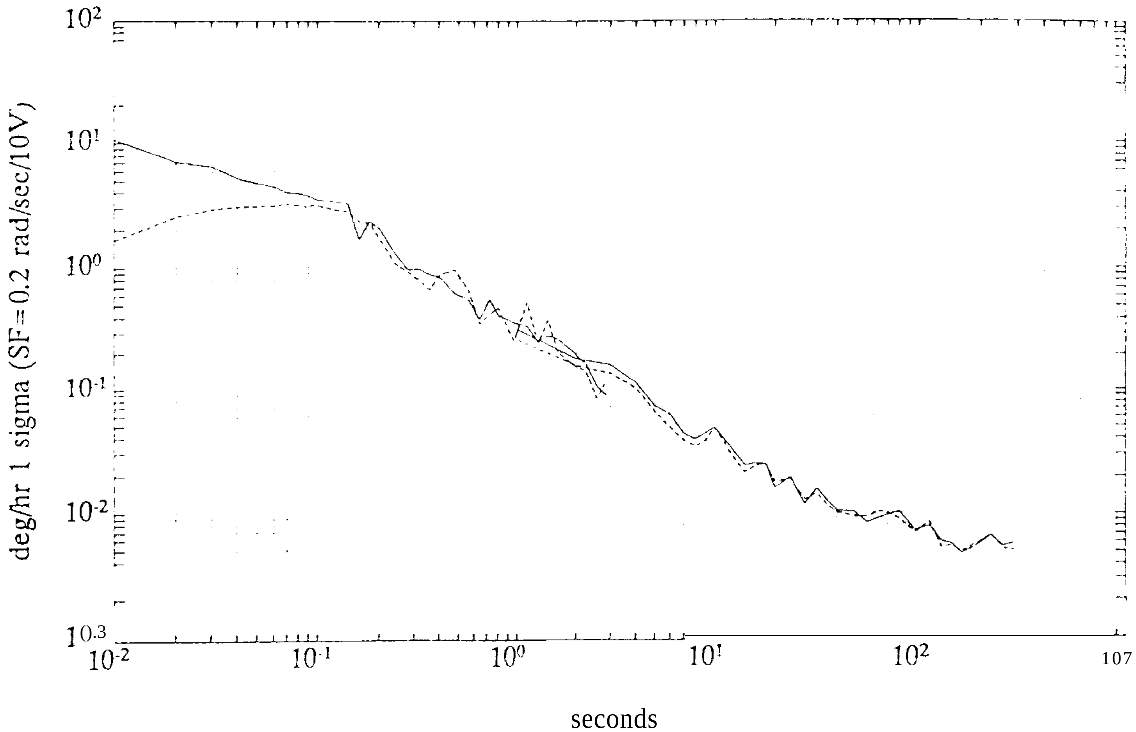
NEA (1 Hz) 10-Jun-94

Date: 10 June
SIRU #: EDU 3
Gyro #: A

SIRU EDU Green Chart Data

The Green Chart below describes the noise and stability characteristics of a SIRU HRG operating with production hardware/software in an EDU system. Filtered and unfiltered rate outputs are shown where "filtered" refers to the 7 Hz IIR output filter. This one-half hour record of data taken under ambient thermal conditions shows approximately 0.005 deg/hr bias stability.

Green Chart of filtered [--] and unfiltered [-] rate



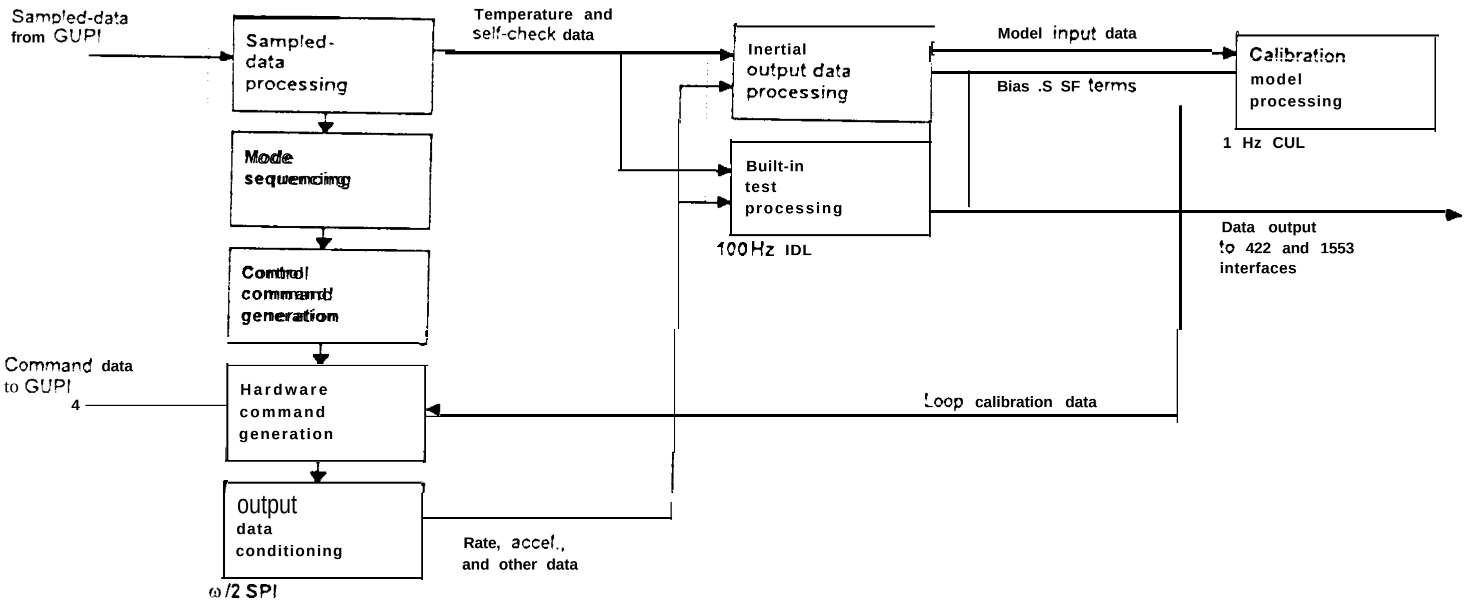
Plan for Long-term Performance Measurement

The SIRU systems integration and calibration team is currently working to complete the tools necessary to perform detailed calibration tests. The execution of this calibration procedure is required in order to generate model coefficients which will be valid during the life of the system. During this development period, short-term temperature profiles (16 hours) are run to provide data which are used to refine the calibration algorithms and demonstrate short-term performance. The simple regression modeling applied to these data sets is useful in identifying error correlations between the SIRU calibration output signals, but is not accurate enough to provide repeatability statistics. The regression process emulates an ideal real-time model and allows us to observe the nature of the small, residual errors. The test program is following the plan summarized below.

- Continue daily tests which reveal the important thermal characteristics that will be included in the final calibration model.
- Perform experiments to determine thermal time constants, magnitude of thermal gradients, and accuracy of the temperature sensor calibration.
- Perform "delta" calibrations in which the system has a subset of model coefficients included in the OFP. These incremental cals improve visibility into the smaller model effects.
- Run a full calibration procedure when test equipment is in place (estimate completion within two weeks). Load OFP cal memory and run back-to-back repeatability tests to generate statistics on the model characteristics and the stability of the "compensated" outputs (estimate one month to complete).

OFP Structure

The Operational Flight Program (OFP) is executed by the GSP and governs all of the control and readout processes. This software is structured around (up to four) signal processing interrupts (SPIs) which independently control each gyro and read out the uncompensated data from both the gyros and accelerometers. While each SPI is processed at 1/2 of the associated gyro flexing frequency, a 100 Hz interface data loop (IDL) accumulates the data into a common time base for external communication. The 1 Hz compensation update loop (CUL) provides slowly varying updates to calibration models which are used to compensate the inertial data.



OFP Compensation Models

The compensation update loop (CUL) generates scale factor, bias, and alignment coefficients based on models **which contain thermal compensation** as well as correlations with other available real-time data. The CUL code specification for these models is shown below with a table of coefficient definitions.

```
GnSF[k] = AngleScaling*(GnSFC0+(GnSFC1
  +GnSFC2*GnFltRTemp[m])*GnFltRTemp[m]
  +(GnSFC3+GnSFC4*GnFltETemp[m])*GnFltETemp[m]
  +(GnSFC5+GnSFC6*GnFltCTemp[m])*GnFltCTemp[m]
  +GnSFC7*GnDeltaParaDrv[m]+GnSFC8*GnDeltaCLQuadDrv[m])
  +GnSFC15*(GnFltRTemp[m]-GnFltCTemp[m])
  +GnSFC16*(GnFltETemp[m]-GnFltCTemp[m])
  +GnSFC17*GnRTempDot[m]+GnSFC18*GnETempDot[m]
  +GnSFC19*GnCTempDot[m]
GnSFNL[k] = AngleScaling*(GnSFC9+(GnSFC10+
  GnSFC11*GnFltETemp[m])*GnFltETemp[m])
GnSFNL2[k] = AngleScaling*(GnSFC12+(GnSFC13
  +GnSFC14*GnFltETemp[m])*GnFltETemp[m])
GnB[k] = AngleScaling*(GnBC0+(GnBC1+
  GnBC2*GnFltRTemp[m])*GnFltRTemp[m]
  +(GnBC3+GnBC4*GnFltETemp[m])*GnFltETemp[m]
  +(GnBC5+GnBC6*GnFltCTemp[m])*GnFltCTemp[m]
  +GnBC7*GnDeltaParaDrv[m]+GnBC8*GnDeltaCLQuadDrv[m])
  +GnBC9*(GnFltRTemp[m]-GnFltCTemp[m])
  +GnBC10*(GnFltETemp[m]-GnFltCTemp[m])
  +GnBC11*GnRTempDot[m]+GnBC12*GnETempDot[m]
  +GnBC13*GnCTempDot[m]
```

Coefficient	Value	Units	2^n	Description
GnSFC0	TBD	rad/sec/10 v	-1	GnSF[k] offset
GnSFC1	TBD	"/deg C	-10	GnSF[k] vs. RTemp
GnSFC2	TBD	"/(deg C)^2	-17	GnSF[k] vs. RTemp^2
GnSFC3	TBD	"/deg C	-10	GnSF[k] vs. ETemp
GnSFC4	TBD	"/(deg C)^2	-17	GnSF[k] vs. ETemp^2
GnSFC5	TBD	"/deg C	-10	GnSF[k] vs. CTemp
GnSFC6	TBD	"/(deg C)^2	-17	GnSF[k] vs. CTemp^2
GnSFC7	TED	"/5 v	-3	G.% SF[k] vs. DeltaParaDrv
GnSFC8	TBD	"/10 V	-3	GnSF[k] vs. DeltaCLQuadDrv
GnSFC15	TBD	"/(deg C)	-7	GnSF[k] vs. RTemp-CTemp
GnSFC16	TBD	"/(deg C)	-7	GnSF[k] vs. ETemp-CTemp
GnSFC17	TED	"/((deg C)/see)	0	GnSF[k] vs. RTempDot
GnSFC18	TBD	"/((deg C)/sec)	0	GnSF[k] vs. ETempDot
GnSFC19	TBD	"/((deg C)/sec)	0	GnSF[k] vs. CTempDot
GnSFC9	TBD	r/s/(10 V)^2	-5	GnSFNL[k] offset
GnSFC10	TBD	"/deg C	-14	GnSFNL[k] vs. ETemp
GnSFC11	TBD	"/(deg C)^2	-21	GnSFNL[k] vs. ETemp^2
GnSFC12	TBD	r/s/(10 V)^3	-5	GnSFNL2[k] offset
GnSFC13	TBD	"/deg C	-14	GnSFNL2[k] vs ETemp
GnSFC14	TBD	"/(deg C)^2	-21	GnSFNL2[k] vs. ETemp^2
GnBC0	TED	rad/sec	-6	GnB[k] offset
GnBC1	TED	"/deg C	-15	GnB[k] vs. RTemp
GnBC2	TBD	"/(deg C)^2	-22	GnB[k] vs. RTemp^2
GnBC3	TBD	"/deg C	-15	GnB[k] vs ETemp
GnBC4	TBD	"/(deg C)^2	-22	GnB[k] vs. ETemp^2
GnBC5	TBD	"/deg C	-15	GnB[k] vs. CTemp
GnBC6	TBD	"/(deg C)^2	-22	GnB[k] vs. CTemp^2
GnBC7	TED	"/5 v	-9	GnB[k] vs. DeltaParaDrv
GnBC8	TBD	"/10 v	-8	GnB[k] vs. DeltaCLQuadDrv
GnBC9	TBD	"/(deg C)	-12	GnB[k] vs. RTemp - CTemp
GnBC10	TBD	"/(deg C)	-12	GnB[k] vs. ETemp-CTemp
GnBC11	TED	"/((deg C)/see)	-5	GM[k] vs. RTempDot
GnBC12	TED	"/((deg C)/see)	-5	GnB[k] vs. ETempDot
GnBC13	TED	"/((deg C)/see)	-5	GnB[k] vs. CTempDot

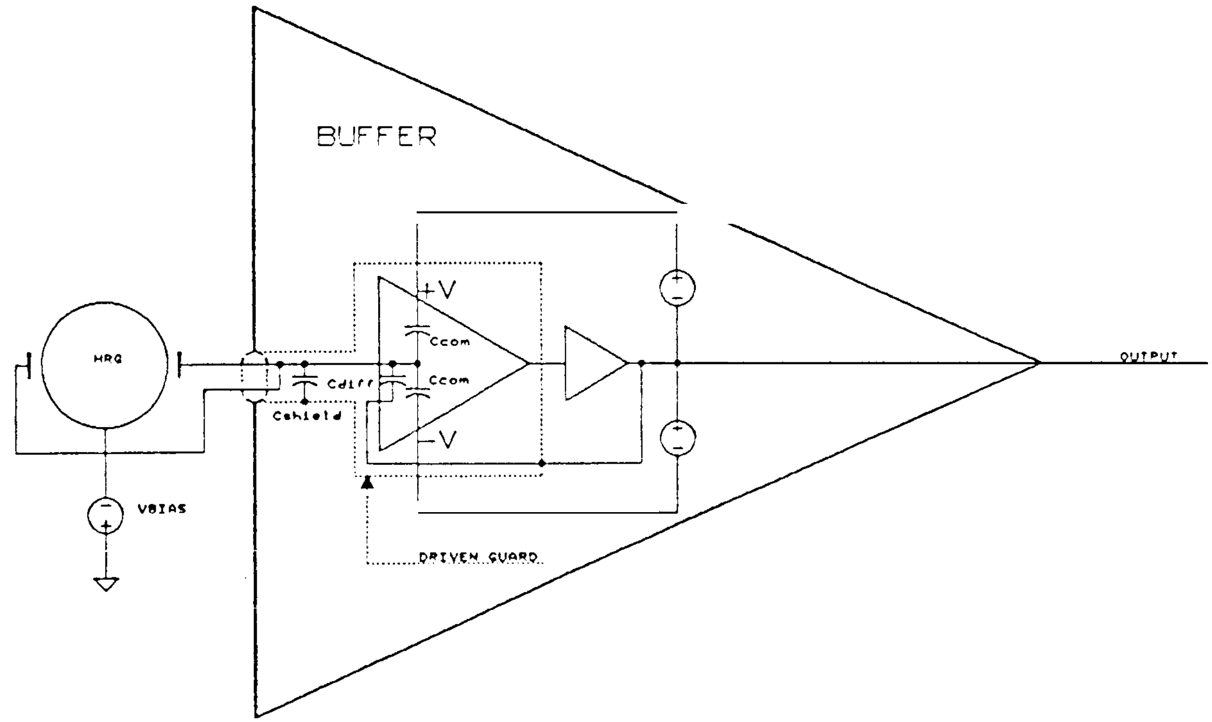
Sensor Electronics — Analog

Buffer Amplifier

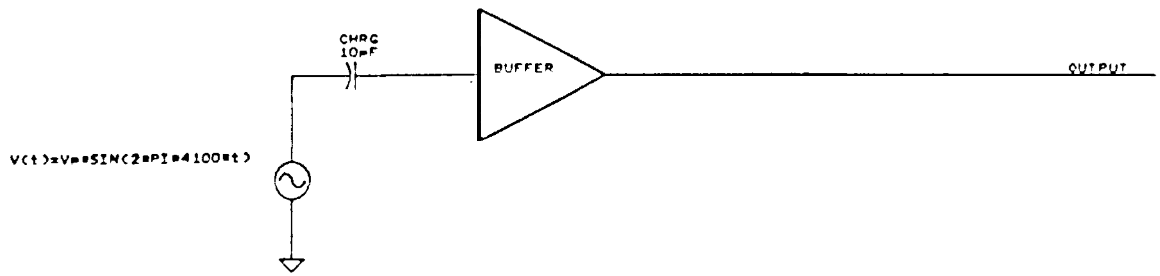
Key Elements/Design Requirements

- Unity gain amplifier
- Very high input resistance (>100 gigaohms) at resonant frequ-ency
- Guarded input
  - Against parasitic (interface and amplifier) capacitance

HRG Buffer Amplifier Block Diagram



EQUIVALENT CIRCUIT

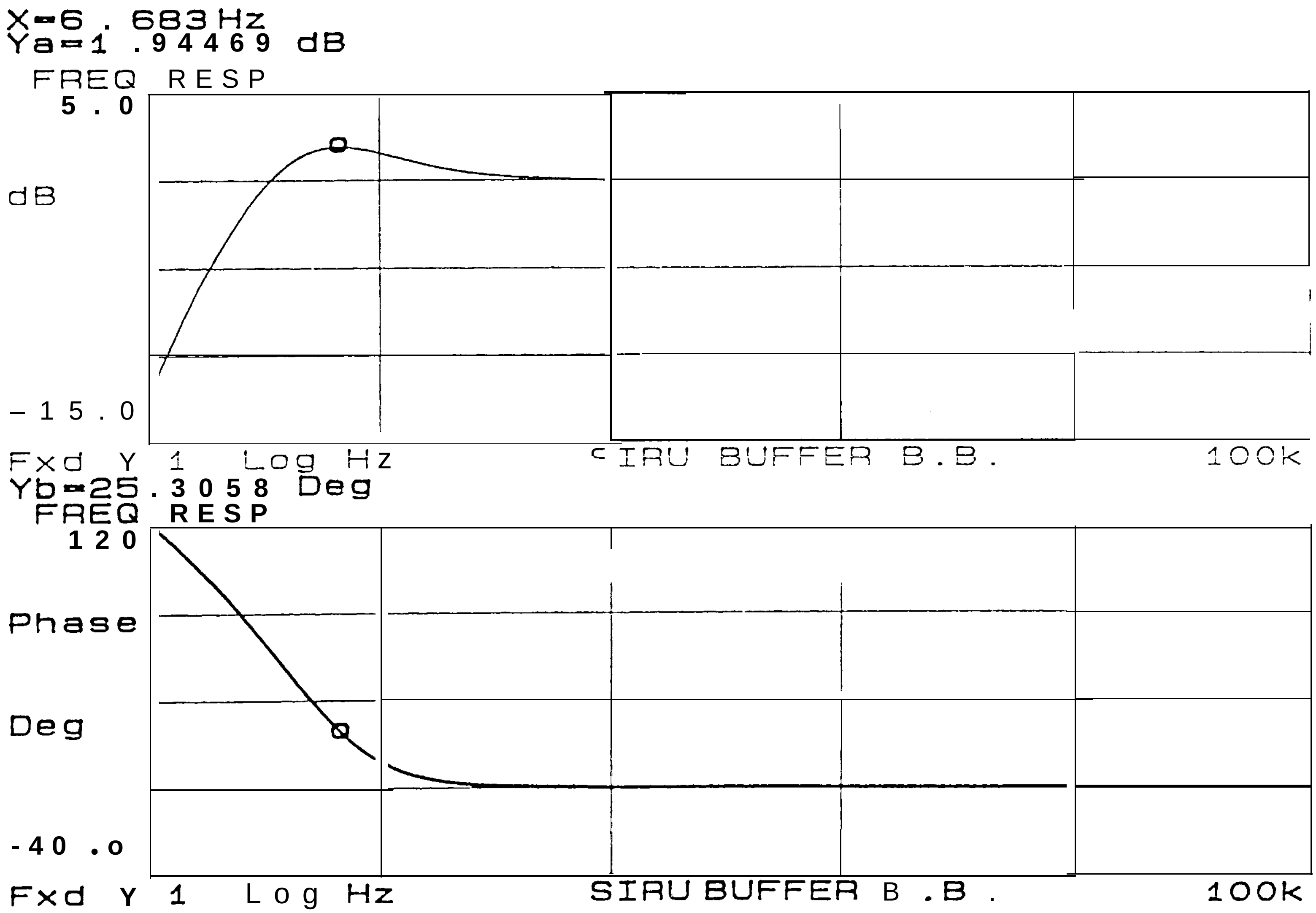


Design Approach

- Eliminate/minimize pickoff interface parasitic capacitances
  - Eliminate input common mode capacitance
    - Uti ize power supply bootstrap echnique on input stage
  - Eliminate differential input capacitance
    - Guarded input stage
    - Driven shield buffer input-to-pickoff

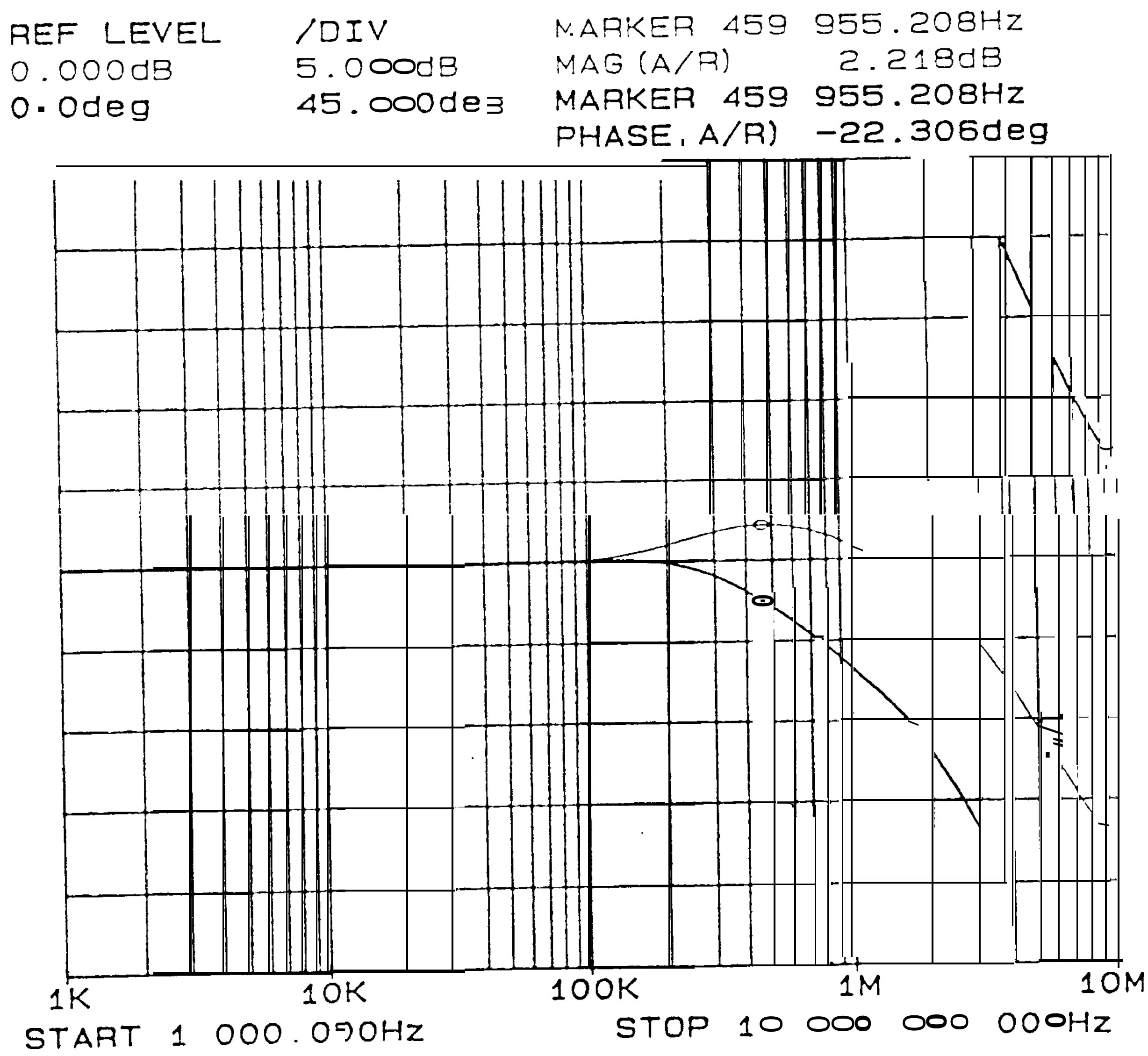
Closed Loop Frequency Response of SIRU Buffer (Test Data)

Low Frequency

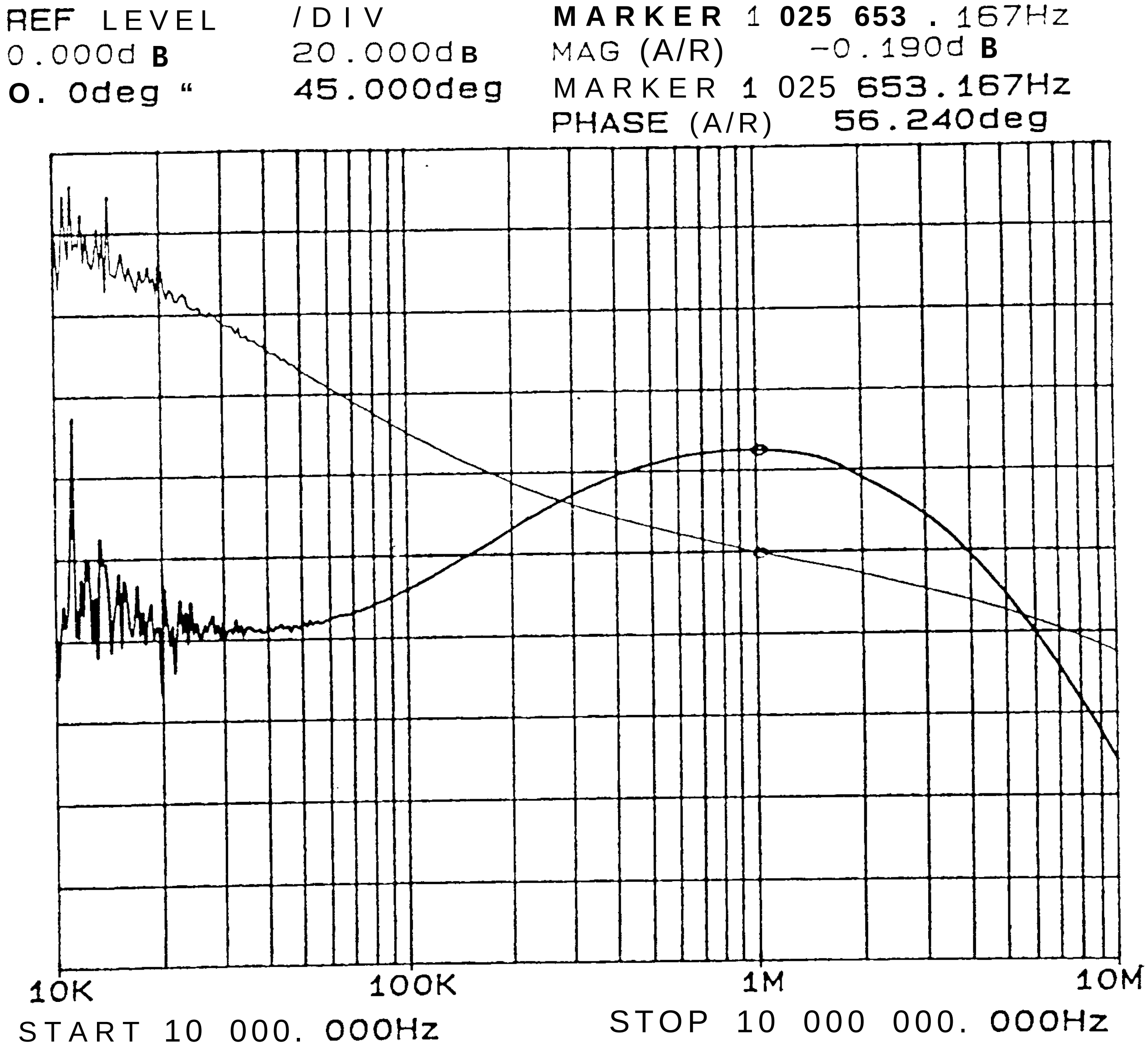


Closed Loop Frequency Response of SIRU Buffer (Test Data)

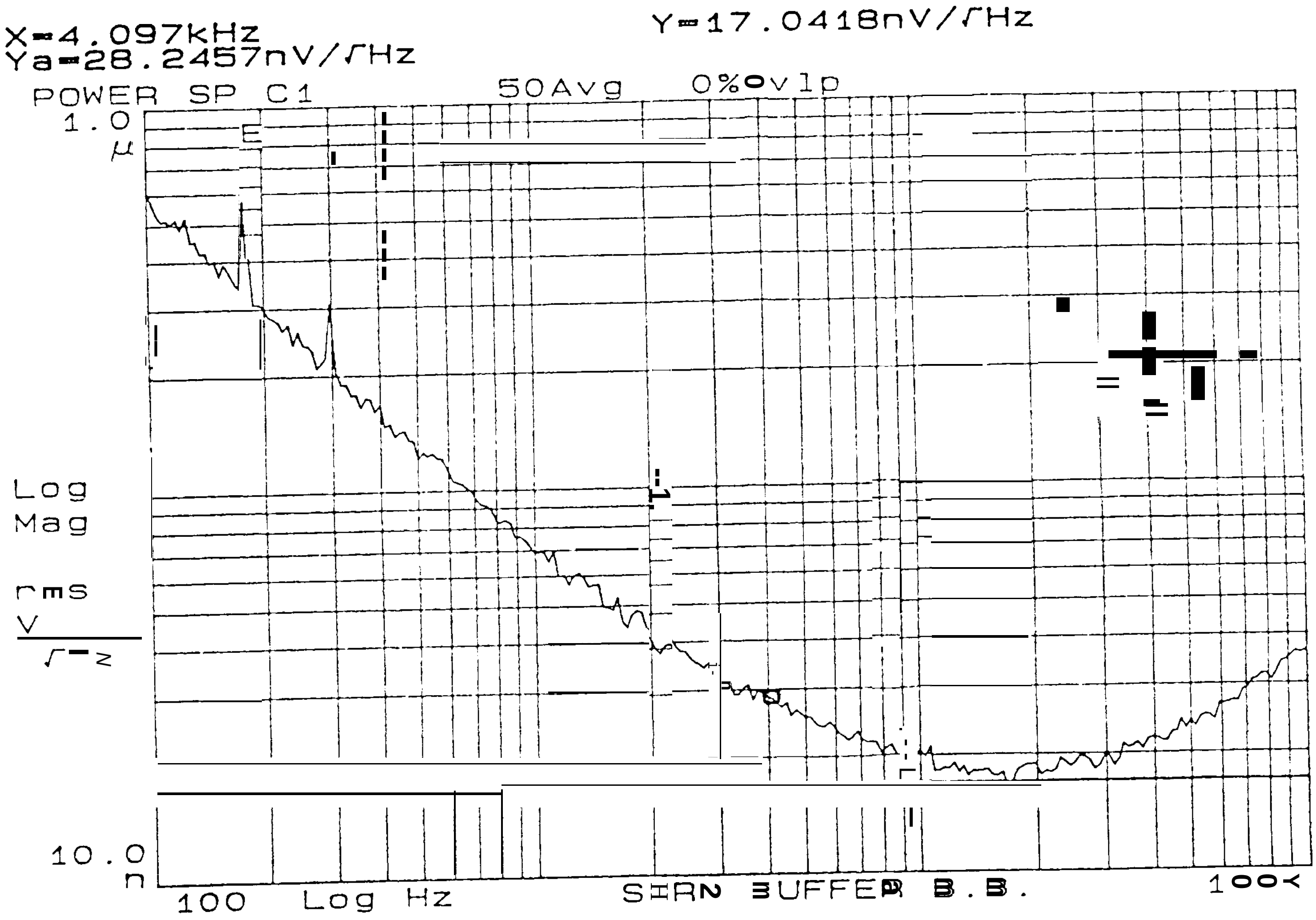
High Frequency



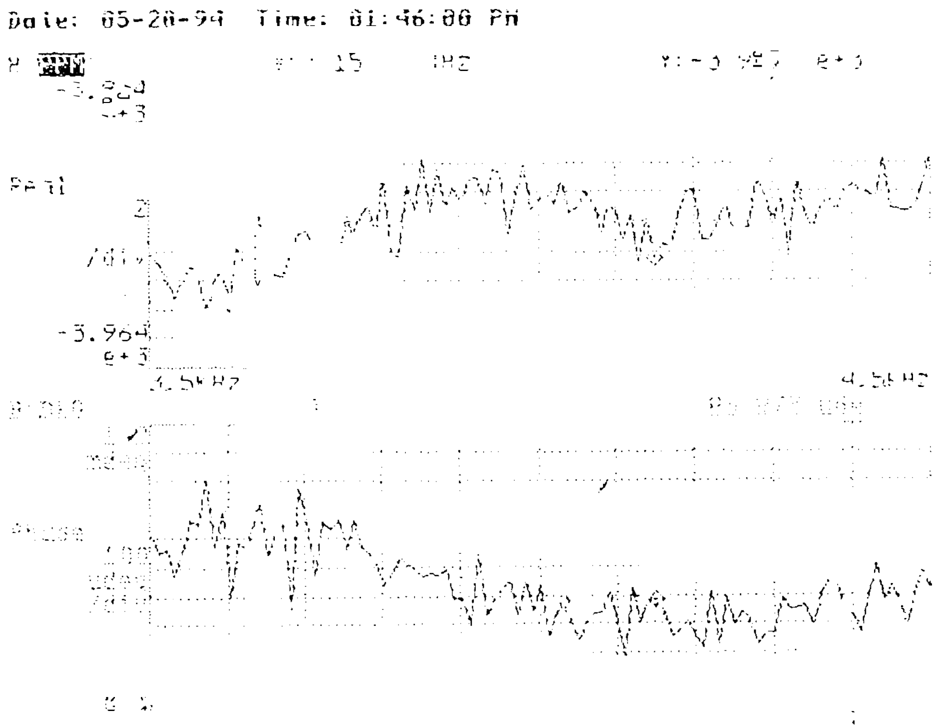
Open Loop Frequency Response of SIRU Buffer (Test Data)

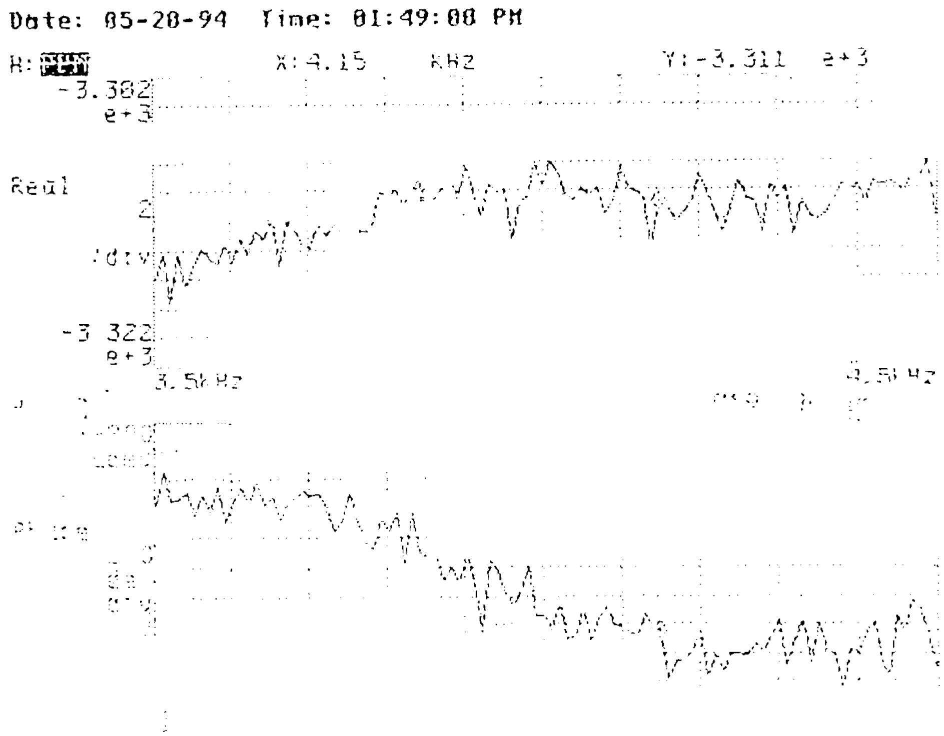


Output Noise PSD
SIRU Buffer (Test Data)



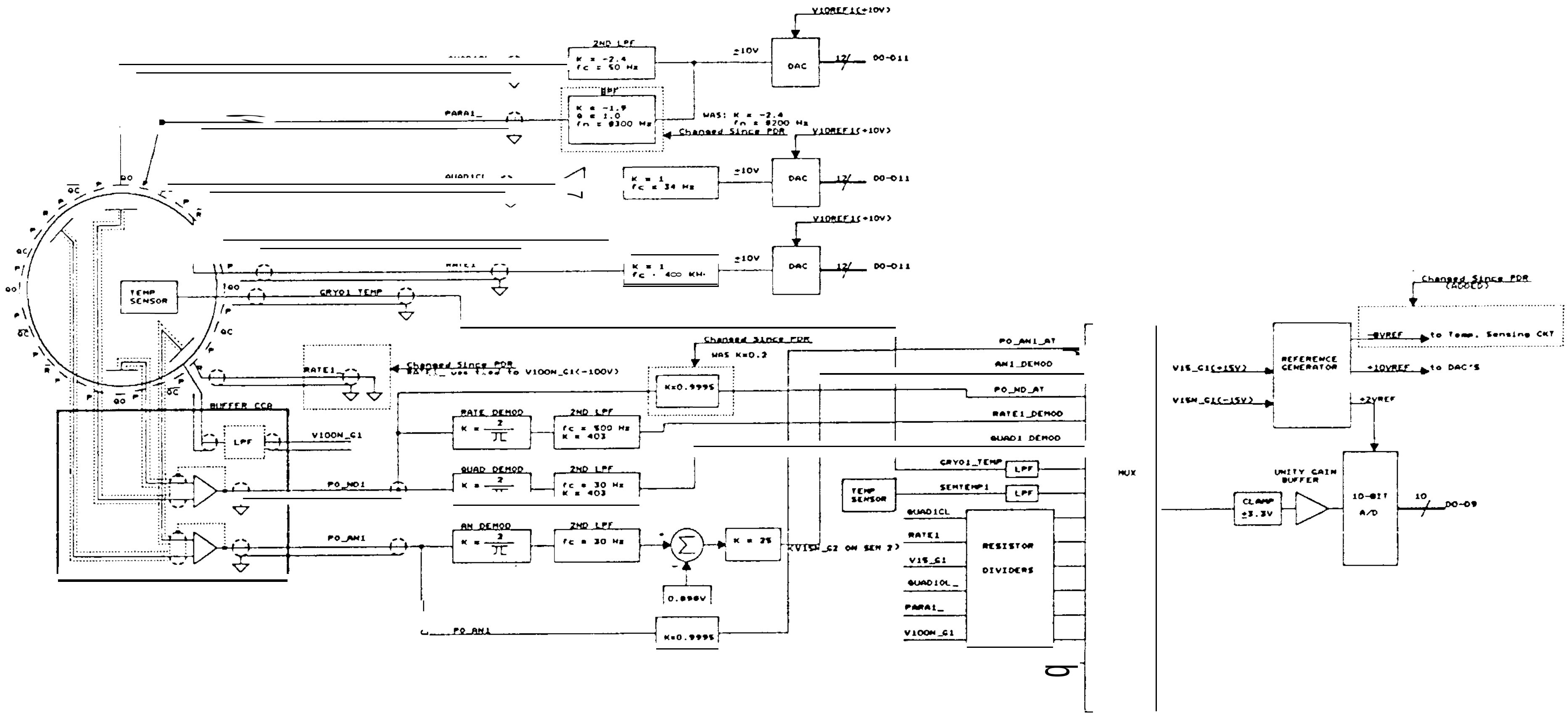
Buffer Real and Phase Test Data



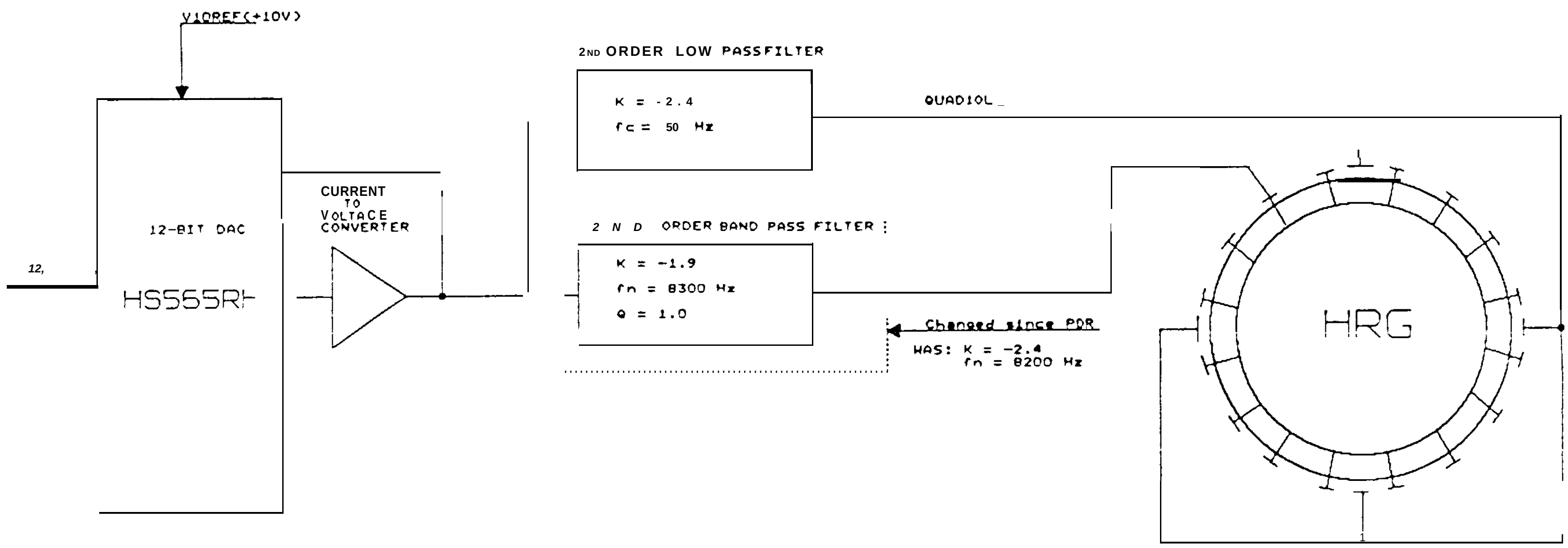


SEM Analog Electronics

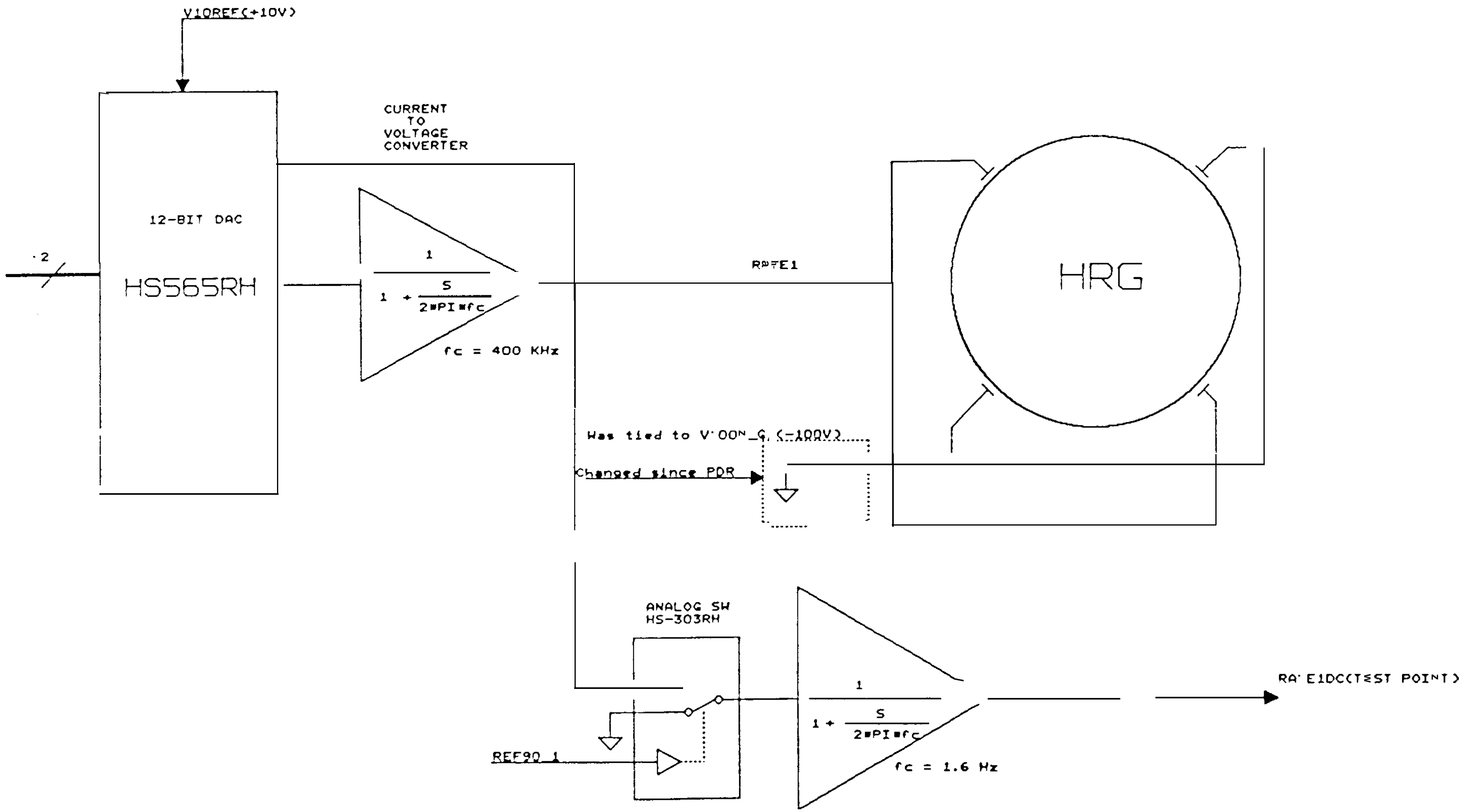
SEM Analog Electronics



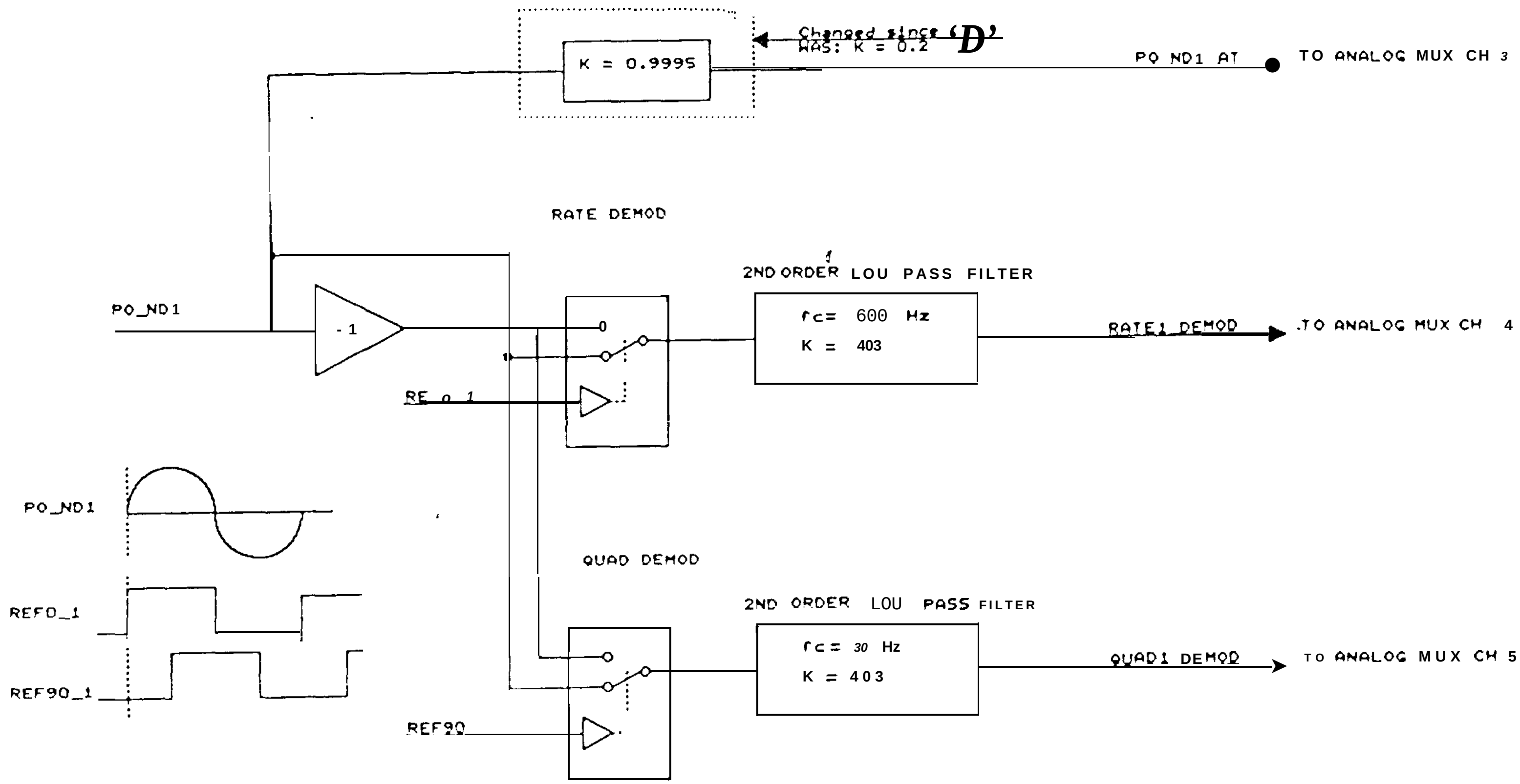
Open Loop Quadrature and Parametric Driver Block Diagram



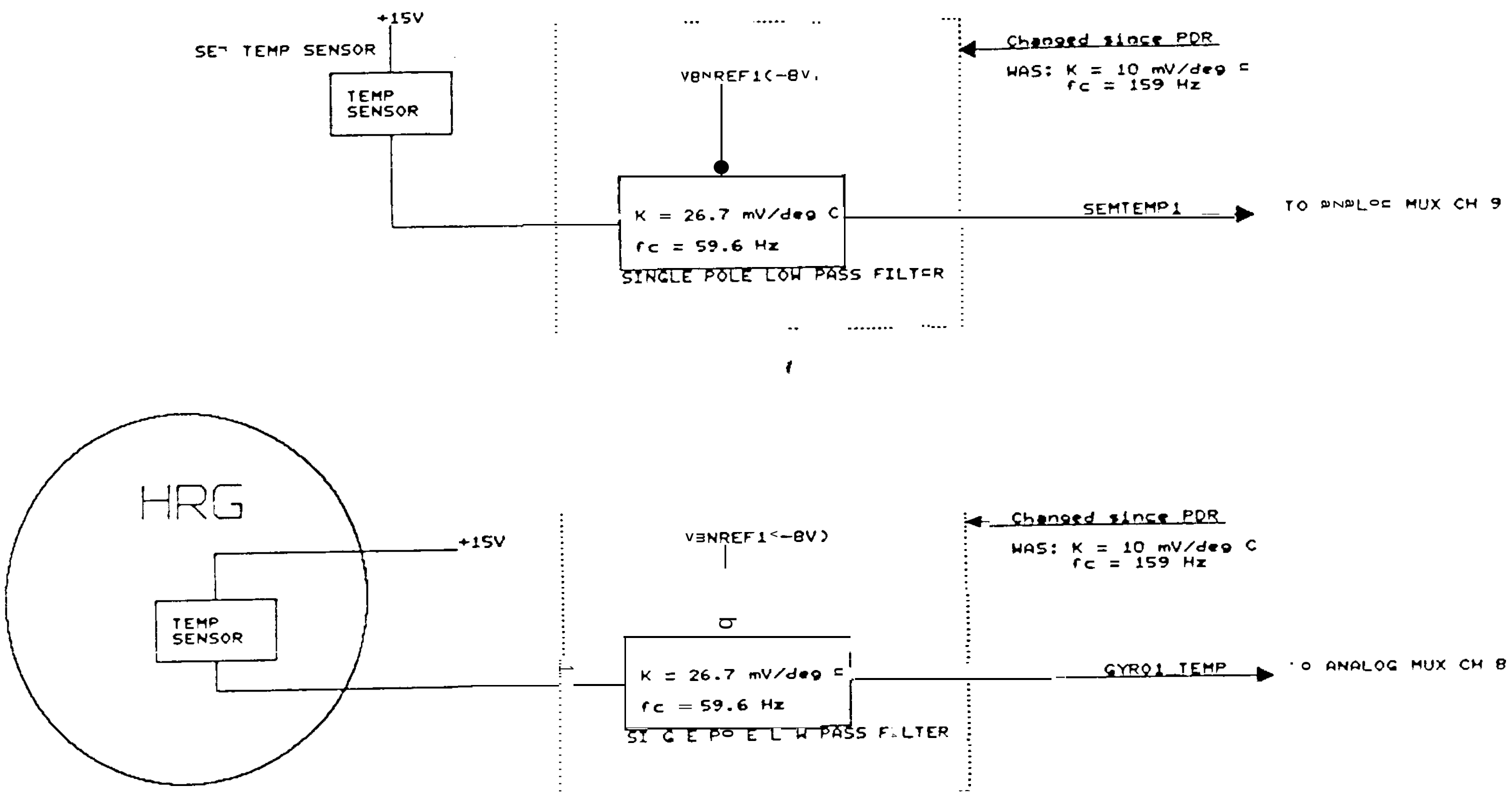
Rate Driver Block Diagram



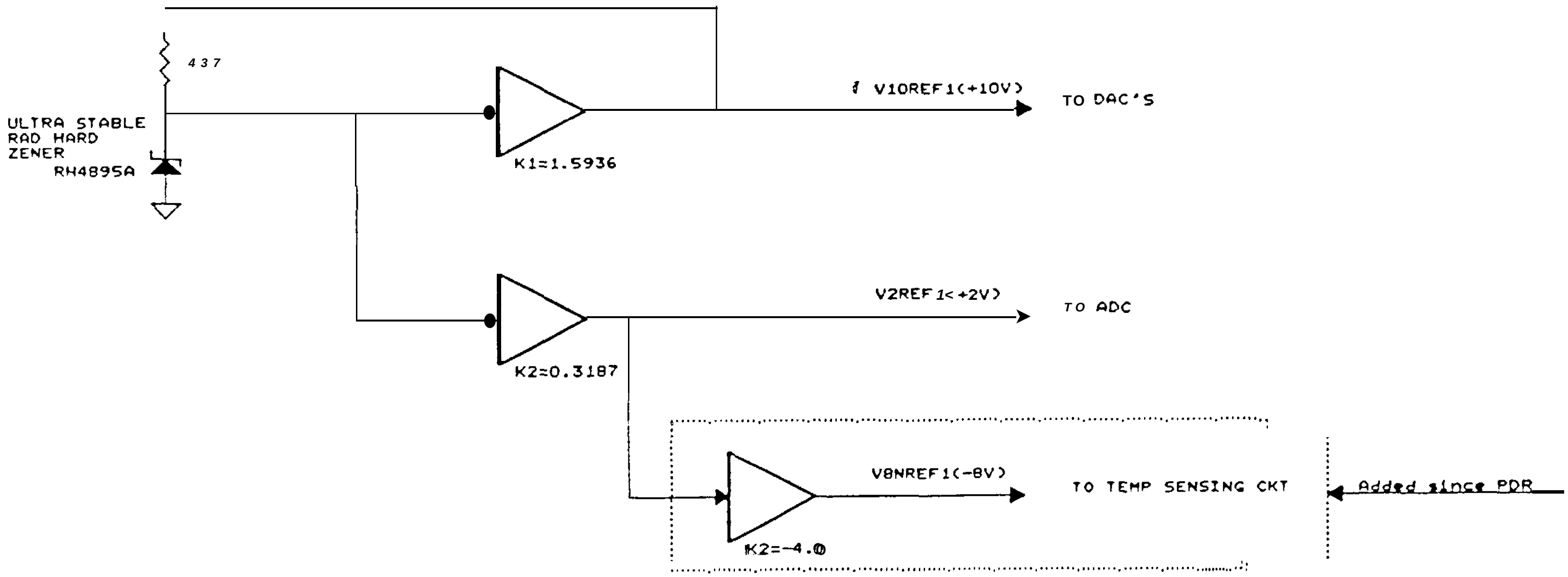
Rate and Quadrature Demodulator Block Diagram



S≷M and Gyro Temperature Monitor ʒ ⊙ck Diagram



Reference Voltage Generator Block Diagram



Cassini IRU Block Diagram
Digital